Hyperion Manual

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CHAPTER 1

Introduction

This is the documentation for Hyperion, a three-dimensional dust continuum Monte-Carlo radiative transfer code. Models are set up via Python scripts, and are run using a compiled Fortran code, optionally making use of the Message Passing Interface (MPI) for parallel computing.

Important: Before you proceed, please make sure you have read the following disclaimers:

- The developers cannot guarantee that the code is bug-free, and users should sign up to the mailing list to ensure that they are informed as soon as bugs are identified and fixed. The developers cannot be held responsible for incorrect results, regardless of whether these arise from incorrect usage, a bug in the code, or a mistake in the documentation.
- Users should read the Important Notes before using Hyperion. In particular, users are fully responsible for ensuring that parameters such as photon numbers and grid resolution are adequate for the problem being studied. Hyperion will *not* raise errors if these inputs are inadequate.

If your work makes use of Hyperion, please cite:

Robitaille, 2011, *HYPERION: an open-source parallelized three-dimensional dust continuum radiative transfer code*, Astronomy & Astrophysics 536 A79 (ADS, BibTeX).

If you need consulting on using Hyperion beyond the current documentation, then please contact me with details of your project.

CHAPTER 2

Note on units and constants

All quantities in Hyperion are expressed in the cgs system. Throughout the documentation, constants are sometimes used in place of values (e.g. `au`, `pc`). These can be imported (in Python) using:

```
from hyperion.util.constants import *
```

or, to control which constants are imported:

```
from hyperion.util.constants import au, pc, lsun
```

See hyperion.util.constants for more details.

CHAPTER 3

Documentation

3.1 Installation

Important: This section contains information on setting up the dependencies for Hyperion as well as Hyperion itself. If you have any issues with the installation of any of the dependencies or Hyperion, please first talk to your system administrator to see if they can help you get set up!

3.1.1 Dependencies

First, you will need to install several dependencies. Please follow the instructions at the following pages to make sure that you have all the dependencies installed.

Fortran code dependencies

Summary of dependencies

The packages required for the Fortran code are:

- A recent Fortran compiler. The following compilers are known to work:
  - gfortran 4.3 and later
  - ifort 11 and later
  - pgfortran 11 and above
- HDF5 1.8.5 or later with the Fortran bindings
- An MPI installation (e.g. MPICH2 or OpenMPI) with the Fortran bindings

Note that often, default installations of HDF5 and MPI packages do not include support for Fortran - this has to be explicitly enabled as described below.

Fortran compiler

The first dependency is a Fortran compiler. In addition to commercial compilers (e.g. `ifort`, `pgfortran`, ...), there are a couple of free ones, the most common of which is `gfortran`. If you don't already have a compiler installed, you can install `gfortran` via package managers on Linux machines, or from MacPorts or binary installers

on Mac (e.g. http://gcc.gnu.org/wiki/GFortranBinaries). If you are unsure about how to do this, speak to your system administrator.

Non-root installs

If you do not have root access to the machine you are using, then replace `/usr/local` in the following instructions by e.g. `$HOME/usr`. In addition, you should never include `sudo` in any of the commands.

Automated Installation

Note: You only need to follow this section if you do **not** have HDF5 or MPI already installed

---

The easiest way to install these dependencies correctly is to use the installation script provided with Hyperion. First, make sure you have downloaded the latest tar file from here, then expand it with:

```
tar xvzf hyperion-x.x.x.tar.gz
cd hyperion-x.x.x
```

Then, go to the `deps/fortran` directory and run the automated install script provided:

```
cd deps/fortran
python install.py <prefix>
```

where `<prefix>` is the folder in which you want to install the MPI and HDF5 libraries. To avoid conflicting with existing installed versions (that may not have Fortran support), it is best to install these in a dedicated directory such as `/usr/local/hyperion`:

```
python install.py /usr/local/hyperion
```

and the libraries will be installed in the `lib`, `include`, etc. directories inside `/usr/local/hyperion`. Once the installation is complete, the installer will instruct you to add certain commands to your startup files.

Note: if you are installing to a location outside your user directory, you will need to run the command with `sudo`, i.e.:

```
sudo python install.py <prefix>
```

Next, open a new terminal and ensure that the following commands:

```
which mpif90
which h5fc
```

return a path that is inside the installation path you specified, for example:

```
$ which mpif90
/usr/local/hyperion/bin/mpif90
$ which h5fc
/usr/local/hyperion/bin/h5fc
```

If you get `command not found` then you have probably not set up your `$PATH` correctly.

The installation script has a number of options (e.g. to set the compilers) that can be seen with:

```
python install.py --help
```

If the installation fails, a log will be posted to the Pastebin service. Copy the URL and report it either by email or on the Github Issues.

If the installation succeeds, you can ignore the rest of this document, and move on to the Python code dependencies.

Manual Installation: MPI

Note: You only need to follow this section if you do **not** have MPI already installed.

In order to use the parallel version of the radiation transfer code, you will need an installation of MPI that supports Fortran. By default, MacOS X ships with OpenMPI, but the Fortran bindings are not included. In this section, I have included instructions to install the MPICH2 library with support for Fortran (though you can in principle use any MPI distribution).

Installation

Note: If you encounter any errors at any stage, see the *Troubleshooting* section.

First, download the source for the latest *stable release* of MPICH2 from the MPI downloads page. Once downloaded, unpack the file and then go into the source directory:

```
cd mpich2-x.x.x
```

and configure the installation:

```
./configure --enable-fc --prefix=/usr/local/mpich2
```

In practice, you will probably want to use a specific fortran compiler, which you can specify using the `F77` and `FC` variables as follows:

```
./configure F77=ifort FC=ifort --enable-fc --prefix=/usr/local/mpich2
```

Once the configure script has successfully run, you can then proceed to build the MPI library:

```
make
```

If the build is successful, then you can install the library into place using:

```
sudo make install
```

Finally, you will need to add the MPICH2 `/usr/local/mpich2/bin` directory to your `$PATH`. To check that the installation was successful, type:

```
which mpif90
```

and you should get:

```
/usr/local/mpich2/bin/mpif90
```

If this is not the case, then the installation was unsuccessful.

Troubleshooting

MacOS 10.5 and ifort If you get the following error when running ./configure:

```
configure: error: ****  Incompatible Fortran and C Object File Types!  ****
F77 Object File Type produced by "ifort  -O2" is : : Mach-O 64-bit object x86_64.
C  Object File Type produced by "gcc  -O2" is : : Mach-O object i386.
```

then you are probably using the 64-bit Intel Fortran Compiler on MacOS 10.5.x, but the 32-bit version of gcc. To fix this, you will need to switch to using the 32-bit Intel Fortran Compiler. First, clean up the installation so far with:

```
make clean
```

Then, rerun configure and build using:

```
./configure F77="ifort -m32" FC="ifort -m32" --enable-fc --prefix=/usr/local/mpich2
make
sudo make install
```

Manual Installation: HDF5

Note: You only need to follow this section if you do **not** have HDF5 already installed.

Installation

Note: If you encounter any errors at any stage, see the *Troubleshooting* section.

To compile the Fortran part of the radiation transfer code, you will need the HDF5 library v1.8.5 or later, with support for Fortran enabled. While package managers such as Fink and MacPorts include HDF5, they often do not include the Fortran bindings. Therefore, it is best to install the HDF5 library manually from source.

To start with, download the source code from the HDF5 downloads page, then go into the source code directory:

```
cd hdf5-x.x.x
```

and configure the installation:

```
./configure --enable-fortran --enable-hl --prefix=/usr/local/hdf5_fortran
```

In practice, you will probably want to use a specific fortran compiler, which you can specify using the `FC` variable as follows:

```
./configure --enable-fortran --enable-hl --prefix=/usr/local/hdf5_fortran FC=ifort
```

Once the configure script has successfully run, you can then proceed to build the HDF5 library:

```
make
```

If the build is successful, then you can install the library into place using:

```
sudo make install
```

Finally, you will need to add the HDF5 `/usr/local/hdf5_fortan/bin` directory to your `$PATH`. To check that the installation was successful, type:

```
which h5fc
```

and you should get:

```
/usr/local/hdf5_fortran/bin/h5fc
```

If this is not the case, then the installation was unsuccessful.

Note: The reason we install HDF5 in `hdf5_fortran` as opposed to simply `hdf5` is so as not to conflict with a possible installation of the library without the Fortran bindings.

Troubleshooting

MacOS 10.5 and ifort If you get the following error when running make:

```
...
H5f90proto.h:1211: warning: previous declaration of 'H5_FC_FUNC_' was here
H5f90proto.h:1216: error: 'H5_FC_FUNC_' declared as function returning a function
H5f90proto.h:1216: warning: redundant redeclaration of 'H5_FC_FUNC_'
H5f90proto.h:1213: warning: previous declaration of 'H5_FC_FUNC_' was here
H5f90proto.h:1218: error: 'H5_FC_FUNC_' declared as function returning a function
H5f90proto.h:1218: warning: parameter names (without types) in function declaration
H5f90proto.h:1218: warning: redundant redeclaration of 'H5_FC_FUNC_'
H5f90proto.h:1216: warning: previous declaration of 'H5_FC_FUNC_' was here
make[3]: *** [H5f90kit.lo] Error 1
make[2]: *** [all] Error 2
make[1]: *** [all-recursive] Error 1
make: *** [all-recursive] Error 1
```

then you are probably using the 64-bit Intel Fortran Compiler on MacOS 10.5.x, but the 32-bit version of gcc. To fix this, you will need to switch to using the 32-bit Intel Fortran Compiler. First, clean up the installation so far with:

```
make clean
```

Then, rerun configure and build using:

```
./configure --enable-fortran --enable-hl --prefix=/usr/local/hdf5_fortran FC="ifort -m32"
make
sudo make install
```

If this does not work, try cleaning again, and setup the 32-bit ifort using the scripts provided with ifort. For example, if you are using ifort 11.x, you can do:

```
make clean
source /opt/intel/Compiler/11.0/056/bin/ia32/ifortvars_ia32.sh
./configure --enable-fortran --enable-hl --prefix=/usr/local/hdf5_fortran FC=ifort
make
sudo make install
```

NAG f95 If you get the following error when running make:

```
Error: H5fortran_types.f90, line 39: KIND value (8) does not specify a valid representation method
Errors in declarations, no further processing for H5FORTRAN_TYPES
[f95 error termination]
make[3]: *** [H5fortran_types.lo] Error 1
make[2]: *** [all] Error 2
make[1]: *** [all-recursive] Error 1
make: *** [all-recursive] Error 1
```

you are using the NAG f95 compiler, which by default does not like statements like `real(8) :: a`. To fix this, you will need to specify the `-kind=byte` option for the f95 compiler. First, clean up the installation so far with:

```
make clean
```

Then, rerun configure and build using:

```
./configure --enable-fortran --enable-hl --prefix=/usr/local/hdf5_fortan FC="ifort -kind=byte"
make
sudo make install
```

Python code dependencies

Summary of dependencies

The packages required for the Python code are:

- Python
- NumPy
- Matplotlib
- h5py
- Astropy

Overview

How you install these depends on your operating system, whether you are an existing Python user, and whether you use package managers. To find out whether any of these are already installed, start up a Python prompt by typing `python` on the command line, then try the following commands:

```
import numpy
import matplotlib
import h5py
import astropy
```

If you see this:

```
>>> import numpy
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
ImportError: No module named numpy
>>>
```

then the module is not installed. If you see this

```
>>> import numpy
>>>
```

then the module is already installed.

Linux

Numpy, Matplotlib, and h5py should be available in most major Linux package managers. If Astropy is not available, you can easily install it from source. To do this, go to the Astropy homepage and download the latest stable version. Then, expand the tar file and install using:

```
tar xvzf astropy-x.x.tar.gz
cd astropy-x.x
python setup.py install
```

Finally, check that Astropy imports cleanly:

```
~> python
Python 2.7.2 (default, Aug 19 2011, 20:41:43) [GCC] on linux2
Type "help", "copyright", "credits" or "license" for more information.
 >>> import astropy
 >>>
```

MacOS X

MacPorts If you are installing Python for the first time, we **strongly** recommend the use of MacPorts to install a full Python distribution. If you would like to do this, follow these instructions to get set up. Once you have your Python distribution installed, make sure all the dependencies for Hyperion are installed:

```
sudo port selfupdate
sudo port install py27-numpy py27-matplotlib py27-h5py py27-astropy
```

If this works, you are all set, and you can move on to the actual *Hyperion* installation instructions.

System/python.org Python

Numpy and Matplotlib If you do not want to use MacPorts, the easiest way to install the two first dependencies is to download and install the MacOS X `dmg` files for NumPy and Matplotlib. Use the links at the top of this section to get the latest `dmg` files from the different websites. You can of course also install these from source, but this is beyond the scope of this documentation.

Note: If you get an error saying *x can't be installed on this disk. x requires Python 2.7 from www.python.org to install*, then this means you are probably just using the system Python installation. Go to www.python.org and download the 2.7.2 version of Python, install, and try installing the packages again.

Check that the packages import correctly:

```
$ python
Python 2.7.2 (default, Jan 31 2012, 22:38:06)
[GCC 4.2.1 (Apple Inc. build 5646)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> import numpy
>>> import matplotlib
>>>
```

If any of the packages are incorrectly installed, they will not import cleanly as above.

h5py Once Numpy and Matplotlib are installed, you will need to install h5py. First, you will need to install the HDF5 library. Note that for the Fortran code, you also need to install the HDF5 library, but here we need to create a clean installation without the fortran bindings, or else h5py will not install properly. Make sure that you perform the following installation in a different directory from before, to avoid overwriting any files.

To install the plain HDF5 library download the source code from the latest HDF5 downloads (choose the hdf5-x.x.x.tar.gz file), then expand the source code:

```
tar xvzf hdf5-x.x.x.tar.gz
cd hdf5-x.x.x
```

and carry out the installation:

```
./configure --prefix=/usr/local/hdf5
make
sudo make install
```

Now, download the latest `h5py-x.x.x.tar.gz` package from the h5py website, and do:

```
tar xvzf h5py-x.x.x.tar.gz
cd h5py-x.x.x
python setup.py build --api=18 --hdf5=/usr/local/hdf5
python setup.py install
```

Now, go back to your home directory, and check that `h5py` imports cleanly:

```
$ python
Python 2.7.2 (default, Jan 31 2012, 22:38:06)
[GCC 4.2.1 (Apple Inc. build 5646)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> import h5py
>>>
```

Astropy Finally, if needed, install Astropy by going to the Astropy homepage and downloading the latest stable version. Then, expand the tar file and install using:

```
tar xvzf astropy-x.x.tar.gz
cd astropy-x.x
python setup.py install
```

Finally, check that Astropy imports cleanly:

```
$ python
Python 2.7.2 (default, Jan 31 2012, 22:38:06)
[GCC 4.2.1 (Apple Inc. build 5646)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> import astropy
>>>
```

Known issues

On recent versions of MacOS X, you may encounter the following error when trying to install the Python library for Hyperion:

```
clang: error: unknown argument: '-mno-fused-madd' [-Wunused-command-line-argument-hard-error-in-futu
```

If this is the case, try setting the following environment variables before installing it:

```
export CFLAGS=-Qunused-arguments
export CPPFLAGS=-Qunused-arguments
```

Alternative CMake build system

An experimental build system for the Fortran binaries based on CMake is now available. The two key advantages with respect to the default build system are:

- support for parallel builds,
- support for dependency tracking (i.e., if a single file in the Hyperion Fortran source is changed, only that file is recompiled).

At the present time, the CMake build system has been tested only on Linux and OSX with the GNU and intel compilers. Support for other platforms will be added in the future.

After having installed CMake, as a first step we are going to create a `build_cmake` directory in the Hyperion root directory:

```
mkdir build_cmake
```

We are going to perform an out-of-source build: all the files generated during the compilation of Hyperion will be kept inside the `build_cmake` directory (so that it easy to start from scratch by simply erasing the build directory).

The next step is the invocation of CMake from the build dir:

```
cd build_cmake
cmake ../
```

CMake will try to identify the Fortran compiler according to some platform-dependent heuristics. If the detected compiler is not the desired one, it is possible to set a custom compiler via the `FC` environment variable. For instance, from bash:

```
FC=ifort cmake ../
```

or:

```
FC=h5pfc cmake ../
```

Note: Normally in order to change the compiler it will be necessary to completely erase the contents of the build directory and start from scratch. This is not necessary when changing other CMake variables such as those discussed below. The compiler variable is special because CMake uses it as a starting point to detect and setup the compilation environment.

CMake will try to locate Hyperion's dependencies (HDF5, MPI) automatically. This usually works fine on Linux systems (where the installation paths are more or less standardised, especially when relying on the system's package manager), but on OSX systems it might be necessary to point CMake to the correct paths. This can be easily done via the text-based CMake GUI, called `ccmake`:

```
ccmake ../
```

After pressing the letter `t` to enter advanced mode, it will be possible to set variables such as `HDF5_hdf5_hl_LIBRARY_RELEASE` to the correct paths on your system.

You might notice that there are other interesting options selectable from the `ccmake` GUI. For instance, the variable `CMAKE_BUILD_TYPE` selects the type of build to perform. The default build type is `Release`; while developing, the `Debug` mode could be more useful. Note that any variable visualised in the GUI can also be set from the command line (see below for some examples). Once all the options have been set, we can run CMake again from the GUI by pressing `c` twice, followed by `g`.

The output of a successful CMake run is a set of Makefiles that can now be used via the standard `make` command (always from the build directory):

```
make
make install
```

It is possible to run the compilation in parallel via the `-j` switch, e.g.,:

```
make -j 8
```

Note that if you edit an existing Fortran file in the Hyperion source tree, you do not need to re-run cmake. Invoking `make` as usual will be enough.

Complete CMake command-line examples

Minimal default configuration:

```
cmake ../
```

Override the compiler:

```
FC=h5pfc cmake ../
```

Override the compiler and set `Debug` mode:

```
FC=h5pfc cmake -DCMAKE_BUILD_TYPE=Debug ../
```

Override the compiler, set `Debug` mode and set custom installation prefix:

```
FC=ifort cmake -DCMAKE_BUILD_TYPE=Debug -DCMAKE_INSTALL_PREFIX=/usr/local ../
```

Note: For instructions for specific computer clusters, see the specific instead, then proceed to the instructions for installing Hyperion below.

3.1.2 Hyperion

Download the latest tar file from here, then expand it with:

```
tar xvzf hyperion-x.x.x.tar.gz
cd hyperion-x.x.x
```

Python module

Install the Python module with:

```
python setup.py install
```

or:

```
python setup.py install --user
```

if you do not have root access. Check that the module installed correctly:

```
$ python
Python 2.7.2 (default, Jan 31 2012, 22:38:06)
[GCC 4.2.1 (Apple Inc. build 5646)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> import hyperion
>>>
```

and also try typing:

```
$ hyperion
```

in your shell. If you get `command not found`, you need to ensure that the scripts installed by Python are in your `$PATH`. If you do not know where these are located, check the last line of the install command above, which should contain something like this:

```
changing mode of /Users/tom/Library/Python/2.7/bin/hyperion to 755
```

The path listed (excluding `hyperion` at the end) should be in your `$PATH`.

Fortran binaries

Compile the Fortran code with:

```
./configure
make
make install
```

By default, the binaries will be written to `/usr/local/bin` (which will require you to use `sudo` for the last command), but you can change this using the `--prefix` option to configure, for example:

```
./configure --prefix=/usr/local/hyperion
```

or:

```
./configure --prefix=$HOME/usr
```

To check that the Fortran binaries are correctly installed, try typing:

```
$ hyperion_sph
Usage: hyperion input_file output_file
```

If you get:

```
$ hyperion_sph
hyperion_sph: command not found
```

then something went wrong in the installation, or the directory to which you installed the binaries is not in your `$PATH`. Otherwise, you are all set!

CMake build system

An experimental build system for the Fortran binaries based on CMake is now available. You can find the detailed instructions on how to use it at the page Alternative CMake build system.

3.2 Important Notes

3.2.1 Gridding

As a user, you are responsible for ensuring that the grid on which the radiative transfer is carried out is adequate to resolve density and temperature gradients. In the case of the *`AnalyticalYSOModel`* class, Hyperion tries to optimize the gridding of the inner disk to ensure that it is properly resolved, but you still need to ensure that the *number* of cells you specificy is adequate.

3.2.2 Number of photons

Similarly to the *Gridding*, you are responsible for choosing an adequate number of photons to carry out the radiative transfer. You can read the Choosing the number of photons wisely page for advice, and this page will be expanded

in future, but the best way to ensure that you have enough photons is to check yourself that the results (temperature, images, SEDs) have converged if you increase the number of photons.

3.2.3 Dust and/or Gas?

While Hyperion is a dust continuum radiative transfer code, you should take care when specifying densities, accretion rates, etc. as to whether to include the contribution from gas. The guidelines are as follows:

- The core Fortran code does not make any assumptions regarding gas - it simply computes optical depths from the densities and opacities provided. Therefore, dust opacities and densities have to be consistent as to whether they are per unit dust mass, or per unit dust+gas mass, and what gas-to-dust ratio they assume.

  For example, if the dust opacities are provided per unit dust mass, then the densities specified in the model should be dust densities. If the dust opacities are provided per unit dust+gas mass, then the densities specified in the model should be dust+gas densities. For the dust models provided in Library of dust models, each dust model explicitly states whether it includes gas in the opacities or not. When setting up your own dust models, you should be aware of whether they are given per unit dust or dust+gas mass and what gas-to-dust ratio was assumed.

- For the *UlrichEnvelope* density structure, the infall rate provided is directly related to the density, so that if the dust opacities are per unit dust mass, the infall rate should be the infall rate of dust.

- For the *AlphaDisk* density structure, the accretion rate provided does not relate to the density in the model, but it used to add a source of luminosity. Therefore, it should include the total mass of **dust+gas** regardless of how the opacities are expressed. However, the mass or density of the disk should be given depending on the units of the opacity, as described above.

3.3 Setting up models

The easiest way to set up models is via the Hyperion Python package. To set up models, you will need to create a Python script, and populate it using the information in this and following sections. Once you have written the script (e.g. `setup_model.py`), you can run it using:

```
python setup_model.py
```

You should start by choosing the type of model you want to set up. At the moment, you can either set up an arbitrary model (which allows you to use an arbitrary grid and density structure), or an analytical YSO model, which is specifically models with fixed density structures such as disks, envelopes, bipolar cavities, and defined on a spherical or cylindrical polar grid. Other kinds of convenience models may be added in future (and contributions are welcome!).

Once you have decided on the type of model, you will need to set up the grid, sources, dust properties, density structure, image and SED parameters, and choose the settings for the radiative transfer algorithm.

The following pages give instructions on setting up the two main kinds of models:

3.3.1 Arbitrary Models

Note: The current document only shows example use of some methods, and does not discuss all the options available. To see these, do not hesitate to use the `help` command, for example `help m.write` will return more detailed instructions on using the `write` method.

To create a general model, you will need to first import the Model class from the Python Hyperion module:

```
from hyperion.model import Model
```

it is then easy to set up a generic model using:

```
m = Model()
```

The model can then be set up using methods of the *Model* instance. These are described in the following sections.

Preparing dust properties

Arguably one of the most important inputs to the model are the dust properties. At this time, Hyperion supports anisotropic wavelength-dependent scattering of randomly oriented grains, using a 4-element Mueller matrix (Chandrasekhar 1960; Code & Whitney 1995). See Section 2.1.3 of Robitaille (2011) for more details.

Note: Because the choice of a dust model is very important for the model, no 'default' dust models are provided with Hyperion, as there is no single sensible default. Instead, you can set up any dust model using the instructions below. In future, a database of published and common dust models will be provided. If you are not sure which dust model to use, or are not familiar with opacities, albedos, and scattering phase functions, you are strongly encouraged to team up with someone who is an expert on the topic of dust, as this should not be left to chance!

There are several ways to set up the dust properties that you want to use, and these are detailed in sections below. In all cases, setting up the dust models is done by first creating an instance of a specific dust class, then setting the properties, and optionally writing out the dust properties to a file:

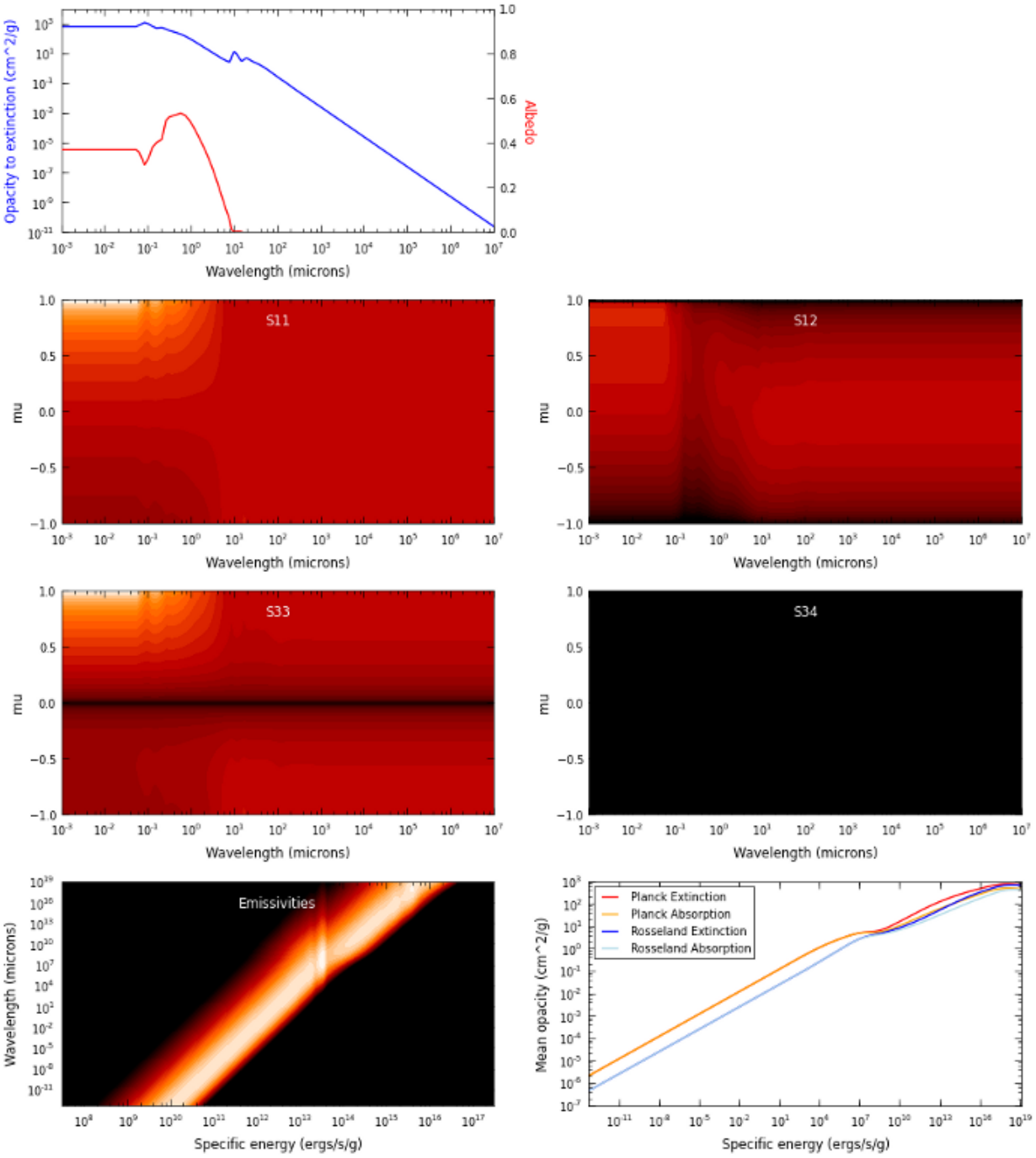
```
from hyperion.dust import SphericalDust
d = SphericalDust()
< set dust properties here >
d.write('mydust.hdf5')
```

Note: Carefully look at the warnings that are raised when writing the dust file, as these may indicate issues that will have an impact on the radiative transfer. See *Common warnings* for more details.

It is also possible to plot the dust properties:

```
d.plot('mydust.png')
```

which gives a plot that can be used to get an overview of all the dust properties:



Important note on units

In all of the following sections, quantities should be specified in the cgs system of units (e.g. cm^2/g for the opacities). Whether the opacities are specified per unit mass of dust or gas is not important, as long as the densities specified when setting up the geometry are consistent. For example, if the opacities are specified per unit dust mass, the densities specified when setting up the model should be dust densities.

Dust with isotropic scattering

Creating a dust object with isotropic scattering properties is very simple. First, import the `IsotropicDust` class:

```
from hyperion.dust import IsotropicDust
```

and create and instance of the class by specifying the frequency, albedo, and opacity to extinction (absorption + scattering):

```
d = IsotropicDust(nu, albedo, chi)
```

where `nu`, `albedo`, and `chi` should be specified as lists or 1-d Numpy arrays, and `nu` should be monotonically increasing. The `albedo` values should all be in the range 0 to 1, and the `chi` values should be positive. The scattering matrix elements will be set to give isotropic scattering, and the emissivities and mean opacities will be set assuming local thermodynamic equilibrium.

Dust with Henyey-Greenstein scattering

Creating a dust object with Henyey-Greenstein scattering properties is very similar to isotropic scattering, with the exception that the scattering parameters have to be specified. The scattering is anisotropic, and the phase function is defined by analytical functions (Henyey & Greenstein, 1941).

First, import the `HenyeyGreensteinDust` class:

```
from hyperion.dust import HenyeyGreensteinDust
```

and create an instance of the class by specifying the frequency, albedo, opacity to extinction (absorption + scattering), and the anisotropy factor and the maximum polarization:

```
d = HenyeyGreensteinDust(nu, albedo, chi, g, p_lin_max)
```

where `nu`, `albedo`, `chi`, `g` and `p_lin_max` should be specified as lists or 1-d Numpy arrays, and `nu` should be monotonically increasing. The `albedo` values should all be in the range 0 to 1, and the `chi` values should be positive. The scattering matrix elements will be set to give the correct phase function for the scattering properties specified, and the emissivities and mean opacities will be set assuming local thermodynamic equilibrium.

Fully customized 4-element dust

While the Henyey-Greenstein scattering phase function allows for anisotropic scattering, it approximates the phase function by analytical equations. In some cases, it is desirable to instead use the full numerical phase function which can be arbitrarily complex.

To set up a fully customized 4-element dust model, first import the `SphericalDust` class (this actually refers to any kind of dust that would produce a 4-element scattering matrix, including randomly oriented non-spherical grains):

```
from hyperion.dust import SphericalDust
```

Then create an instance of this class:

```
d = SphericalDust()
```

Now that you have a dust 'object', you will need to set the optical properties of the dust, which include the albedo and extinction coefficient (in cgs) as a function of frequency (in Hz):

```
d.optical_properties.nu = nu
d.optical_properties.albedo = albedo
d.optical_properties.chi = chi
```

where `nu`, `albedo`, and `chi` should be specified as lists or 1-d Numpy arrays, and `nu` should be monotonically increasing. The `albedo` values should all be in the range 0 to 1, and the `chi` values should be positive.

Once these basic properties are set, you will need to set the scattering properties by setting the matrix elements. These should be specified as a function of the cosine of the scattering angle, `mu`. The values of `mu` should be specified as a 1-d Numpy array:

```
d.optical_properties.mu = mu
```

Once `nu` and `mu` are set, the values of the scattering matrix elements can be set. These are stored in variables named using the convention of Code & Whitney (1995): P1 (equivalent to S11), P2 (equivalent to S12), P3 (equivalent to S44), and P4 (equivalent to -S34). Each of these variables should be specified as a 2-d array with dimensions `(n_nu, n_mu)`, where `n_nu` is the number of frequencies, and `n_mu` is the number of values of the cosine of the scattering angle:

```
d.optical_properties.P1 = P1
d.optical_properties.P2 = P2
d.optical_properties.P3 = P3
d.optical_properties.P4 = P4
```

Alternatively, it is possible to call:

```
d.optical_properties.initialize_scattering_matrix()
```

After which `P1`, `P2`, `P3`, and `P4` will be set to arrays with the right dimensions, and with all values set to zero. You could for example set up an isotropic scattering matrix by setting the values of the arrays:

```
d.optical_properties.P1[:, :] = 1.
d.optical_properties.P2[:, :] = 0.
d.optical_properties.P3[:, :] = 1.
d.optical_properties.P4[:, :] = 0.
```

If nothing else is specified, the dust emissivity will be set assuming local thermodynamic equilibrium (i.e. it will be set to the opacity to absorption times Planck functions).

Emissivities

By default, emissivities and mean opacities will be calculated under the assumption of local thermodynamic equilibrium for 1200 dust temperatures between 0.1 and 100000K, but this can be customized, as described below.

LTE emissivities To set the LTE emissivities manually, you can call the `set_lte_emissivities` method. For example, to calculate the emissivities for 1000 temperatures between 0.1 and 2000K, you can do:

```
d.set_lte_emissivities(n_temp=1000,
                       temp_min=0.1,
                       temp_max=2000.)
```

The more temperatures the emissivities are calculated for, the more accurate the radiative transfer (Hyperion interpolates between emissivities, rather the picking the closest one) but the slower the dust file will be to generate and read into Hyperion.

Custom emissivities If you want to specify fully customized emissivities as a function of specific energy, you can instead do this by directly accessing the variables, which are stored as attributes to `d.emissivities`, i.e.:

```
d.emissivities.nu
d.emissivities.var
d.emissivities.jnu
d.emissivities.var_name
```

The attribute `nu` should be set to a 1-d array giving the frequencies that the emissivities are specified for, `var` should be set to another 1-d array containing the values of the specific energy the emissivities are defined for, and `jnu` should be set to a 2-d array with dimensions `(len(nu), len(var))` giving the emissivities. In addition, you will need to set `var_name` to `'specific_energy'` (in future, other kinds of emissivity variables may be supported). For example, to set a constant emissivity as a function of frequency and specific energy, you can do:

```
d.emissivities.nu = np.logspace(8., 16., 100)  # 100 values between 10^8 and 10^16
d.emissivities.var = np.logspace(-2., 8., 20)  # 20 values of the specific energy
                                               # between 10^-2 and 10^8
d.emissivities.jnu = np.ones(100, 20)  # constant emissivities
d.emissivities.var_name = 'specific_energy'
```

Extrapolating optical properties

In some cases (see e.g. *Common warnings*) it can be necessary to extrapolate the dust properties to shorter and/or longer wavelengths. While it would be preferable to do this extrapolation properly before passing the values to the dust objects, in some cases the extrapolation is relatively straightforward, and you can make use of the following extrapolation convenience functions:

```
d.optical_properties.extrapolate_wav(0.1, 1000)
d.optical_properties.extrapolate_nu(1.e5, 1.e15)
```

In the first case, the extrapolation is done by specifying wavelengths in microns, and in the second case by specifying the frequency (in Hz).

The extrapolation is done in the following way:

- The opacity to extinction (`chi`) is extrapolated by fitting a power-law to the opacities at the two highest frequencies and following that power law, and similarly at the lowest frequencies. This ensures that the slope of the opacity remains constant.
- The albedo is extrapolated by assuming that the albedo is constant outside the original range, and is set to the same value as the values for the lowest and highest frequencies.
- The scattering matrix is extrapolated similarly to the albedo, by simply extending the values for the lowest and highest frequencies to the new frequency range.

The plots shown higher up on this page have made use of these extrapolation methods.

Common warnings

One of the most common warnings when computing the LTE emissivities or writing out a dust file is the following:

```
WARNING: Planck function for lowest temperature not completely covered by opacity function
WARNING: Planck function for highest temperature not completely covered by opacity function
```

The LTE emissivity is set to $\kappa_\nu B_\nu(T)$, so you need to ensure that the opacity is defined over a frequency large enough to allow this to be calculated from the lowest to the highest temperatures used for the LTE emissivities. The default range is quite large (0.1 to 100000K) so you can either reduce this range (see *LTE emissivities*) or you should define the optical properties over a larger frequency range (see *Extrapolating optical properties* for one way to do this).

More specifically, the frequency range should extend almost three orders of magnitude above the peak frequency for the coldest temperature, and one order of magnitude below the peak frequency for the hottest temperature. For the default temperature range for the LTE emissivities (0.1 to 100000K), this means going from about 5e7 to 5e16Hz (or 0.5nm to 5m) which is a huge frequency range, over which dust properties are often not known. However, in most cases, a sensible extrapolation of the properties you have should be fine - the plots shown higher up on this page show the values extrapolated to the required range. If you restrict yourself to a smaller temperature range (e.g. 3 to 1600K) you can also reduce the required range significantly.

Note: If you do not fix this warning, the normalization of the emissivities will be off, and the results from the radiative transfer may be incorrect!

Writing dust files without the Python library

If for any reason you wish to write the HDF5 dust files directly without using the Hyperion Python library, you can find a detailed description of the format in Dust HDF5 Format.

Coordinate grids and physical quantities

In general, coordinate grids and density grids are set using methods of the form:

```
from hyperion.model import Model
m = Model()
m.set_<grid_type>_grid(...)
m.add_density_grid(density, dust)
```

where `<grid_type>` is the grid type being used, and `dust` is a dust file in HDF5 format specified either by filename, or as a dust object. See Preparing dust properties for more details about creating and using dust files. For example, if you are using a dust file named `kmh.hdf5`, you can specify this with:

```
m.add_density_grid(density, 'kmh.hdf5')
```

The `add_density_grid` method can be called multiple times if multiple density arrays are needed (for example if different dust sizes have different spatial distributions).

Note: If you haven't already done so, please make sure you read the Important Notes to understand whether to specify dust or dust+gas densities!

Optionally, a specific energy distribution can also be specified in `add_density_grid` using the `specific_energy=` argument:

```
m.add_density_grid(density, dust, specific_energy=specific_energy)
```

where `specific_energy` is given in the same format as `density` (see sections below). By default, the specific energy specified is the *initial* specific energy used, and if the number of temperature iterations is not zero (see *Specific energy calculation*) this specific energy gets replaced with the self-consistently calculated one in later iterations. If instead you want this specific energy to be *added* to the self-consistently computed one after each iteration, see *Initial and additional specific energy*.

Hyperion currently supports six types of 3-d grids:

- Cartesian grids
- Spherical polar grids
- Cylindrical polar grids

- AMR (Adaptive Mesh Refinement) grids
- Octree grids
- Voronoi grids

The following sections show how the different kinds of grids should be set up.

Regular 3-d grids

Geometry In the case of the cartesian and polar grids, you should define the wall position in each of the three directions, using cgs units for the spatial coordinates, and radians for the angular coordinates. These wall positions should be stored in one 1-d NumPy array for each dimension, with one element more than the number of cells defined. The walls can then be used to create a coordinate grid using methods of the form `set_x_grid(walls_1, walls_2, walls_3)`. The following examples demonstrate how to do this for the various grid types

- A 10x10x10 cartesian grid from -1pc to 1pc in each direction:

```
x = np.linspace(-pc, pc, 11)
y = np.linspace(-pc, pc, 11)
z = np.linspace(-pc, pc, 11)
m.set_cartesian_grid(x, y, z)
```

- A 2-d 400x200x1 spherical polar grid with radial grid cells logarithmically spaced between one solar radius and 100AU, and the first grid cell wall located at 0:

```
r = np.logspace(np.log10(rsun), np.log10(100 * au), 400)
r = np.hstack([0., r])  # add cell wall at r=0
theta = np.linspace(0., pi, 201)
phi = np.array([0., 2 * pi])
m.set_spherical_polar_grid(r, theta, phi)
```

- A 3-d 100x100x10 cylindrical polar grid with radial grid cells logarithmically spaced between one solar radius and 100AU, and the first grid cell wall located at 0:

```
w = np.logspace(np.log10(rsun), np.log10(100 * au), 100)
w = np.hstack([0., w])  # add cell wall at w=0
z = np.linspace(-10 * au, 10 * au, 101)
phi = np.linspace(0, 2 * pi, 11)
m.set_cylindrical_polar_grid(w, z, phi)
```

Note: Spherical and cylindrical polar grids do not have to start at `r=0` or `w=0`, but you need to make sure that all sources are located inside the grid. For example, if you place a point source at the origin, you will need the first grid cell wall to be at `r=0` or `w=0`. In the above cases, since the grid cell walls are distributed logarithmically, the first grid cell wall has to be added separately, hence the use of `hstack`, which is used to add a 0 at the start of the array.

Density and Specific Energy For regular cartesian and polar grids, a 3-d NumPy array containing the density array is required, for example:

```
m.add_density_grid(np.ones((100,100,100)), 'kmh.hdf5')
```

for a 100x100x100 grid. Due to Numpy array conventions, the dimensions should be specified in reverse order, i.e. `(n_z, n_y, n_x)` for a cartesian grid, `(n_phi, n_theta, n_r)` for a spherical polar grid, or `(n_phi, n_z, n_r)` for a cylindrical polar grid.

Note that once you have set the grid geometry on a model, you can access variables that make it easy (if you wish) to set up densities from analytical equations:

- `m.grid.gx`, `m.grid.gy`, and `m.grid.gz` for cartesian grids
- `m.grid.gr`, `m.grid.gt`, and `m.grid.gp` for spherical polar grids
- `m.grid.gw`, `m.grid.gz`, and `m.grid.gp` for cylindrical polar grids

These variables are the coordinates of the center of the cells, and each of these variables is a full 3-d array. For example, `m.grid.gx` is the x position of the center of *all* the cells, and has the same shape as the density array needs to have. In addition, the `m.grid.shape` variable contains the shape of the grid. This makes it easy to use analytical prescriptions for the density. For example, to set up a sphere of dust with radius R in a cartesian grid, you could do:

```
density = np.zeros(m.grid.shape)
density[(m.grid.gx ** 2 + m.grid.gy ** 2 + m.grid.gz ** 2) < R ** 2] = 1.
```

This grid would have a density of 0 outside R, and 1 inside R. Note that of course you should probably be using a spherical polar grid if you want to set up a sphere of dust, but the above example can be applied to more complicated analytical dust structures.

AMR grids

Geometry AMR grids have to be constructed using the *`AMRGrid`* class:

```
from hyperion.grid import AMRGrid
amr = AMRGrid()
```

Levels can be added with:

```
level = amr.add_level()
```

And grids can be added to a level with:

```
grid = level.add_grid()
```

Grid objects have the following attributes which should be set:

- `xmin` - lower x position of the grid
- `xmax` - upper x position of the grid
- `ymin` - lower y position of the grid
- `ymax` - upper y position of the grid
- `zmin` - lower z position of the grid
- `zmax` - upper z position of the grid
- `nx` - number of cells in x direction
- `ny` - number of cells in y direction
- `nz` - number of cells in z direction
- `quantities` - a dictionary containing physical quantities (see below)

Once we have an AMR grid object, which we call `amr` here, the geometry can be set using:

```
m.set_amr_grid(amr)
```

The `quantities` attribute is unimportant for this step, as long as the geometry is correct.

For more details on how to create or read in an AMR object, and for a list of requirements and restrictions on the geometry, see *AMR Grids*.

Note: If you load in your simulation data with the yt package, you can make use of the *from_yt()* method to easily convert the simulation into a Hyperion *AMRGrid* object.

Density and Specific Energy Since AMR grids have a more complex structure than regular 3-d arrays, the density should be added using an *AMRGrid* object. In this case, the `quantity` attribute should be set for each grid object. For each physical quantity in the AMR grid, the dictionary should have an entry of the form:

```
grid.quantities[<quantity>] = quantity_array
```

where `<quantity>` is a string containing the name of the quantity (e.g. `density`) and `quantity_array` should be a Numpy array with dimensions `(grid.nz, grid.ny, grid.nx)` (see *AMR Grids* for more details).

When calling `add_density_grid`, the density should be specified as an item of the *AMRGrid* object:

```
m.add_density_grid(amr_object['density'], dust_file)
```

for example:

```
m.add_density_grid(amr['density'], 'kmh.hdf5')
```

Specific energies can be specified using the same kinds of objects and using the `specific_energy` argument:

```
m.add_density_grid(amr['density], dust_file,
                   specific_energy=amr['specific_energy'])
```

Note that in this example, the `amr` object contains the geometry, the density, and the specific energy (i.e. it is not necessary to create a separate *AMRGrid* object for each one).

Octree grids

Geometry An Octree is a hierarchical grid format where each cell can be divided into eight children cells. At the top level is a single cell that covers the whole spatial domain being considered. To set up an Octree, the following information is needed:

- `x`, `y`, `z` - the coordinates of the center of the parent cell
- `dx`, `dy`, `dz` - the size of the parent cell
- `refined` a 1-d sequence of booleans giving the structure of the grid.

The `refined` sequence contains all the information regarding the hierarchy of the grid, and is described in *Octree Grids*. Once this sequence is set, the geometry can be set with:

```
m.set_octree_grid(x, y, z, dx, dy, dz, refined)
```

Density and Specific Energy Densities (and optionally specific energies) should be specified in the same manner as the regular grids, but should be specified as a 1-d Numpy array with the same length as the `refined` list, where each density value corresponds to the equivalent cell in the `refined` list. Density values for cells with `refined` set to `True` will be ignored, and can be set to zero.

Voronoi grids

Geometry A Voronoi grid is based on the concept of 3D Voronoi diagrams. A Voronoi grid is created from a set of user-specified seed points. Each seed point corresponds to a single grid cell, and the cell in which a seed point is located is defined geometrically by the set of all points closer to that seed than to any other.

Voronoi cells are always guaranteed to be convex polyhedra. The number and distribution of the seed points are arbitrary (clearly, for best results the values of these two parameters should be chosen following some physical intuition or with a specific goal in mind - e.g., seed points could be more numerous where higher resolution is needed).

In order to set up a Voronoi grid, the following information is needed:

- `x`, `y`, `z` - three 1-d Numpy arrays of equal size representing the coordinates of the seed points. The size of these arrays implicitly defines the number of seed points.

The geometry can be set with:

```
m.set_voronoi_grid(x, y, z)
```

Density and Specific Energy Densities (and optionally specific energies) should be specified in the same manner as the regular grids, but should be specified as a 1-d Numpy array with the same length as the number of seed points. Each density value in the array refers to the cell containing the corresponding seed point.

Luminosity sources

General notes

Sources can be added to the model using methods of the form `m.add_*_source()`. For example adding a point source can be done with:

```
source = m.add_point_source()
```

These methods return a source 'object' that can be used to set and modify the source parameters:

```
source = m.add_point_source()
source.luminosity = lsun
source.temperature = 10000.
source.position = (0., 0., 0.)
```

Note: It is also possible to specify the parameters using keyword arguments during initialization, e.g.:

```
m.add_point_source(luminosity=lsun, temperature=10000.,
                   position=(0., 0., 0.))
```

though this can be longer to read for sources with many arguments.

All sources require a luminosity, given by the `luminosity` attribute (or `luminosity=` argument), and the emission spectrum can be defined in one of three ways:

- by specifying a spectrum using the `spectrum` attribute (or `spectrum=` argument). The spectrum should either be a `(nu, fnu)` pair or an instance of an `atpy.Table` with two columns named `'nu'` and `'fnu'`. For example, given a file `spectrum.txt` with two columns listing frequency and flux, the spectrum can be set using:

```
import numpy
spectrum = np.loadtxt('spectrum.txt', dtype=[('nu', float),
                                             ('fnu', float)])
source.spectrum = (spectrum['nu'], spectrum['fnu'])
```

- by specifying a blackbody temperature using the `temperature` attribute (or `temperature=` argument). This should be a floating point value.
- by using the local dust emissivity if neither a spectrum or temperature are specified.

Note: By default, the number of photons emitted is proportional to the luminosity, so in cases where several sources with very different luminosities are included in the models, some sources might be under-sampled. You can instead change the configuration to emit equal number of photons from all sources - see *Multiple sources* for more details.

Point sources

A point source is defined by a luminosity, a 3-d cartesian position (set to the origin by default), and a spectrum or temperature. The following examples demonstrate adding different point sources:

- Set up a 1 solar luminosity 10,000K point source at the origin:

```
source = m.add_point_source()
source.luminosity = lsun  # [ergs/s]
source.temperature = 10000.  # [K]
```

- Set up two 0.1 solar luminosity 1,300K point sources at +/- 1 AU in the x direction:

```
# Set up the first source
source1 = m.add_point_source()
source1.luminosity = 0.1 * lsun  # [ergs/s]
source1.position = (au, 0, 0)  # [cm]
source1.temperature = 1300.  # [K]

# Set up the second source
source2 = m.add_point_source()
source2.luminosity = 0.1 * lsun  # [ergs/s]
source2.position = (-au, 0, 0)  # [cm]
source2.temperature = 1300.  # [K]
```

- Set up a 10 solar luminosity source at the origin with a spectrum read in from a file with two columns giving wavelength (in microns) and monochromatic flux:

```
# Use NumPy to read in the spectrum
import numpy as np
data = np.loadtxt('spectrum.txt', dtype=[('wav', float), ('fnu', float)])

# Convert to nu, fnu
nu = c / (data['wav'] * 1.e-4)
fnu = data['fnu']

# Set up the source
source = m.add_point_source()
source.luminosity = 10 * lsun  # [ergs/s]
source.spectrum = (nu, fnu)
```

Note: Regardless of the grid type, the coordinates for the sources should always be specified in cartesian coordinates, and in the order `(x, y, z)`.

If you want to set up many point sources (for example for a galaxy model) you may instead want to consider using a *Point source collections*.

Spherical sources

Adding spherical sources is very similar to adding point sources, with the exception that a radius can be specified:

```
source = m.add_spherical_source()
source.luminosity = lsun  # [ergs/s]
source.radius = rsun  # [cm]
source.temperature = 10000.  # [K]
```

It is possible to add limb darkening, using:

```
source.limb = True
```

Spots on spherical sources

Adding spots to a spherical source is straightforward. Spots behave the same as other sources, requiring a luminosity, spectrum, and additional geometrical parameters:

```
source = m.add_spherical_source()
source.luminosity = lsun  # [ergs/s]
source.radius = rsun  # [cm]
source.temperature = 10000.  # [K]

spot = source.add_spot()
spot.luminosity = 0.1 * lsun  # [ergs/s]
spot.longitude = 45.  # [degrees]
spot.latitude = 30.  # [degrees]
spot.radius = 5.  # [degrees]
spot.temperature = 20000.  # [K]
```

Diffuse sources

Diffuse sources are defined by a total luminosity, and a probability distribution map for the emission, defined on the same grid as the density. For example, if the grid is defined on a 10x10x10 grid, the following will add a source which emits photons from all cells equally:

```
source = m.add_map_source()
source.luminosity = lsun  # [ergs/s]
source.map = np.ones((10, 10, 10))
```

By default, if no spectrum or temperature is provided, photons will be emitted using the local emissivity of the dust. However, you can also specify either a temperature or a spectrum as for *Point Sources* and *Spherical Sources*, e.g:

```
source.temperature = 10000.  # [K]
```

or:

```
source.spectrum = (nu, fnu)
```

Note: The `map` array does not need to be normalized.

External sources

There are two kinds of external illumination sources, spherical and box sources - the former being more suited to spherical polar grids, and the latter to cartesian, AMR, and octree grids (there is no cylindrical external source for cylindrical grids at this time). In both cases, photons are emitted inwards isotropically. For example, an external spherical source can be added with:

```
source = m.add_external_spherical_source()
source.luminosity = lsun  # [ergs/s]
source.radius = pc  # [cm]
source.temperature = 10000.  # [K]
```

As for point and spherical sources, the position of the center can also be set, and defaults to the origin. External box sources have a `bounds` attribute instead of `radius` and `position`:

```
source = m.add_external_box_source()
source.luminosity = lsun  # [ergs/s]
source.bounds = [[-pc, pc], [-pc, pc], [-pc, pc]]  # [cm]
source.temperature = 10000.  # [K]
```

where the `bounds` attribute is given as `[[xmin, xmax], [ymin, ymax], [zmin, zmax]]`.

See How to set the luminosity for an external radiation field for information on setting the luminosity correctly in order to reproduce a given intensity field.

Note: Even though these sources are referred to as 'external', they have to be placed inside the outermost walls of the grid. The sources are not box-shared source or spherical source that can be placed outside the grid, but rather sources that emit inwards instead of outwards, making it possible to simulate an external radiation field.

Plane parallel sources

Finally, it is possible to add circular plane parallel sources (essentially a circular beam with a given origin and direction):

```
source = m.add_plane_parallel_source()
source.luminosity = lsun  # [ergs/s]
source.radius = rsun  # [cm]
source.temperature = 10000.  # [K]
source.position = (au, 0., 0.)  # [cm]
source.direction = (45., 0.)  # [degrees]
```

where `direction` is a tuple of (theta, phi) that gives the direction of the beam.

Point source collections

In cases where you want to set up more than a few dozen point sources, it may be worth instead using a point source collection, which can contain an arbitrary number of point sources with different luminosities, and a common temperature or spectrum. To add a point source collection, use e.g.:

```
source = m.add_point_source_collection()
```

The attributes are the same as for the *Point Sources* but the `source.luminosity` attribute should be set to an array with as many elements as sources, and the `source.position` attribute should be set to a 2-d array where the first dimension matches `source.luminosity`, and with 3 elements in the second dimension (x, y, and z). The following example shows how to set up 1000 random point sources with random positions from -1au to 1au in all directions, and with random luminosities between 0 and lsun:

```
N = 1000
x = np.random.uniform(-1., 1, N) * au
y = np.random.uniform(-1., 1, N) * au
z = np.random.uniform(-1., 1, N) * au
```

```
source = m.add_point_source_collection()
source.luminosity = np.random.random(N) * lsun
source.position = np.vstack([x, y, z]).transpose()
source.temperature = 6000.
```

In terms of photon sampling, a point source collection acts as a single source with a luminosity given by the sum of the components - so if you have one point source collection and one spherical source with the same total luminosity, the number of photons will be evenly split between the two. Within the point source collection, the number of photons is split according to luminosity.

Setting up images and SEDs

There are two main kinds of images/SEDs that can be produced for each model: images/SEDs computed by binning the photons as they escape from the density grid, and images/SEDs computed by peeling off photon packets at each interaction into well defined directions. The latter provide more accurate SEDs and much better signal-to-noise, and are likely to be more commonly used than the former.

The code currently allows at most one set of binned images, and any number of sets of peeled images. A set is defined by a wavelength range, image resolution and extent, and any number of viewing angles.

Creating a set of images

To add a set of binned images/SEDs to the model, use:

```
image = m.add_binned_images()
```

and to create a set of peeled images/SEDs to the model, use:

```
image = m.add_peeled_images()
```

Only one set of binned images can be added, but any number of sets of peeled image can be added. In general, peeled images are recommended because binned images suffer from low signal-to-noise, and angle averaging of images.

The wavelength range (in microns) for the images/SEDs should be specified using:

```
image.set_wavelength_range(n_wav, wav_min, wav_max)
```

The image size in pixels and the extent of the images should be specified using:

```
image.set_image_size(n_x, n_y)
image.set_image_limits(xmin, xmax, ymin, ymax)
```

where the image limits should be given in cm. The apertures for the SEDs can be specified using:

```
image.set_aperture_radii(n_ap, ap_min, ap_max)
```

where the radii should be given in cm. If this is not specified, the default is to have one aperture with infinite size, i.e. measuring all the flux.

For binned images, the number of bins in the theta and phi direction should be specified using:

```
image.set_viewing_bins(10, 10)
```

whereas for peeled images, the viewing angles should be specified as lists or arrays of theta and phi values, in degrees. For example, the following produces images from pole-on to edge-on at constant phi using 20 viewing angles:

```
# Set number of viewing angles
n_view = 20

# Generate the viewing angles
theta = np.linspace(0., 90., n_view)
phi = np.repeat(45., n_view)

# Set the viewing angles
image.set_viewing_angles(theta, phi)
```

Note: For peeled images, the number of viewing angles directly impacts the performance of the code - once the specific energy/temperature has been computed, the code will then run approximately in a time proportional to the number of viewing angles.

Uncertainties

Uncertainties can be computed for SEDs/images (doubling the memory/disk space required):

```
image.set_uncertainties(True)
```

Stokes components

By default, to save memory and disk space, the Stokes components other than I for the images are not saved. To enable the storage of the Stokes components other than I, make use of the `set_stokes` method:

```
sed.set_stokes(True)
```

or:

```
image.set_stokes(True)
```

If you do not do this, then you will not be able to make use of the `stokes=` option in *`get_sed()`* and *`get_image()`*.

Note: In Hyperion 0.9.3 and earlier versions, this option did not exist and Stokes components were all saved by default. Note that the default behavior is now changed. However, files produced in Hyperion 0.9.3 and earlier will behave as if the option was set to *True* for backward-compatibility.

File output

Finally, to save space, images can be written out as 32-bit floats instead of 64-bit floats. To write them out as 32-bit floats, use:

```
image.set_output_bytes(4)
```

and to write them out as 64-bit floats, use:

```
image.set_output_bytes(8)
```

Tracking photon origin

SEDs/images can also be split into emitted/thermal or scattered components from sources or dust (4 combinations). To activate this, use:

```
image.set_track_origin('basic')
```

It is also possible to split the SED into individual sources and dust types:

```
image.set_track_origin('detailed')
```

For example, if five sources and two dust types are present, there will be 14 components in total: five for photons emitted from sources, two for photons emitted from dust, five for photons emitted from sources and subsequently scattered, and two for photons emitted from dust and subsequently scattered.

Finally, it is also possible to split the photons as a function of how many times they scattered:

```
image.set_track_origin('scatterings', n_scat=5)
```

where `n_scat` gives the maxmimum number of scatterings to record.

See *Post-processing models* for information on how to extract this information from the output files.

Note: If you are using the *`AnalyticalYSOModel`* class and are interested in separating the disk, envelope, and other components, but are using the same dust file for the different components, these will by default be merged prior to the radiative transfer calculation, so you will need to set `merge_if_possible=False` when calling *`write()`* to prevent this (see *`write()`* for more information).

Disabling SEDs or Images

When adding a set of binned or peeled images, it is possible to disable the SED or image part:

```
image = m.add_binned_images()  # Images and SEDs
image = m.add_binned_images(image=False)  # SEDs
image = m.add_binned_images(sed=False)  # Images

image = m.add_peeled_images()  # Images and SEDs
image = m.add_peeled_images(image=False)  # SEDs
image = m.add_peeled_images(sed=False)  # Images
```

Advanced

A few more advanced parameters are available for peeled images, and these are described in Advanced settings for peeled images.

Example

The following example creates two sets of peeled SEDs/images. The first is used to produce an SED with 250 wavelengths from 0.01 to 5000. microns with uncertainties, and the second is used to produce images at 5 wavelengths between 10 and 100 microns, with image size 100x100 and extending +/-1pc in each direction:

```
image1 = m.add_peeled_images(image=False)
image1.set_wavelength_range(250, 0.01, 5000.)
image1.set_uncertainties(True)
```

```
image2 = m.add_peeled_images(sed=False)
image2.set_wavelength_range(5, 10., 100.)
image2.set_image_size(100, 100)
image2.set_image_limits(-pc, +pc, -pc, +pc)
```

Radiative transfer settings

Once the coordinate grid, density structure, dust properties, and luminosity sources are set up, all that remains is to set the parameters for the radiation transfer algorithm, including number of photons to use, or whether to use various optimization schemes.

Number of photons

The number of photons to run in various iterations is set using the following method:

```
m.set_n_photons(initial=1000000, imaging=1000000)
```

where `initial` is the number of photons to use in the iterations for the specific energy (and therefore temperature), and `imaging` is the number of photons for the SED/image calculation, whether using binned images/SEDs or peeling-off.

In addition, the `stats=` argument can be optionally specified to indicate how often to print out performance statistics (if it is not specified a sensible default is chosen).

Since the number of photons is crucial to produce good quality results, you can read up more about setting sensible values at Choosing the number of photons wisely.

Specific energy calculation

To set the number of initial iterations used to compute the dust specific energy, use e.g.:

```
m.set_n_initial_iterations(5)
```

Note that this can also be zero, in which case the temperature is not solved, and the radiative transfer calculation proceeds to the image/SED calculation (this is useful for example if one is making images at wavelengths where thermal emission is negligible, or if a specific energy/temperature was specified as input).

It is also possible to tell the radiative transfer algorithm to exit these iterations early if the specific energy has converged. To do this, use:

```
m.set_convergence(True, percentile=100., absolute=0., relative=0.)
```

where the boolean value indicates whether to use convergence detection (`False` by default), and `percentile`, `absolute`, and `relative` arguments are explained in more detail in Section 2.4 of Robitaille (2011). For the benchmark problems of that paper, the values were set to:

```
m.set_convergence(True, percentile=99., absolute=2., relative=1.02)
```

which are reasonable starting values. Note that if you want to use convergence detection, you should make sure that the value for `set_n_initial_iterations` is not too small, otherwise the calculation might stop before converging. When running the main Hyperion code, convergence statistics are printed out, and it is made clear when the specific energy has converged.

Initial and additional specific energy

Another option that is related to the specific energy is *set_specific_energy_type()*. This is used to control how any specific energy passed to *add_density_grid()* is used. By default, the specific energy specified is the *initial* specific energy used, and if the number of temperature iterations is not zero (see *Specific energy calculation*) this specific energy gets replaced with the self-consistently calculated one in later iterations. If instead you want this specific energy to be *added* to the self-consistently computed one after each iteration, you can set:

```
m.set_specific_energy_type('additional')
```

This can be used for example if you need to take into account an additional source of heating that cannot be modelled by Hyperion.

Raytracing

To enable raytracing (for source and dust emission, but not scattering), simply use:

```
m.set_raytracing(True)
```

This algorithm is described in Section 2.6.3 of Robitaille (2011). If raytracing is used, you will need to add the `raytracing_sources` and `raytracing_dust` arguments to the call to `set_n_photons`, i.e.:

```
m.set_n_photons(initial=1000000, imaging=1000000,
                raytracing_sources=1000000, raytracing_dust=1000000)
```

Diffusion

If the model density contains regions of very high density where photons get trapped or do not enter, one can enable the modified random walk (MRW; Min et al. 2009, Robitaille 2010) in order to group many photon interactions into one. The MRW requires a parameter `gamma` which is used to determine when to start using the MRW (see Min et al. 2009 for more details). By default, this parameter is set to `1`. The following example shows how to enable the modified random walk, and set the gamma parameter to `2`:

```
m.set_mrw(True, gamma=2.)
```

In some cases (such as protoplanetary disks) very optically thick regions do not receive any radiation. In cases where the temperature in these regions is important, one can use the partial diffusion approximation (PDA; Min et al. 2009) to solve the diffusion equation over the grid and find the missing temperatures:

```
m.set_pda(True)
```

Note however that if more than 10,000 cells have low photon counts and require the PDA, this can be **very** slow, so this option is only recommended in cases where you know it is absolutely needed. In most cases, if photons cannot reach inside certain cells, these cells are unlikely to be contributing a significant amount of flux to SEDs or images.

Dust sublimation

To set whether and how to sublimate dust, first the dust file needs to be read in (or initialized in the script), the sublimation parameters should be set, and the dust object should be passed directly to add_density:

```
from hyperion.dust import SphericalDust

d = SphericalDust('kmh.hdf5')
d.set_sublimation_temperature('fast', temperature=1600.)
```

```
m.add_density_grid(density, d)
```

The first argument of `set_sublimation_temperature` can be `none` (dust sublimation does not occur), `cap` (temperatures in excess of the one specified will be reset to the one given), `slow` (dust with temperatures in excess of the one specified will be gradually destroyed), or `fast` (dust with temperatures in excess of the one specified will be immediately destroyed). For more information, see Section 2.7.3 of Robitaille (2011).

Multiple sources

By default, the number of photons emitted is proportional to the luminosity of the sources, so in cases where several sources with very different luminosities are included in the models, some sources might be under-sampled. In some cases, this will not be a problem, but in some cases you may want to emit equal numbers of photons from each source instead. For example, if you have two sources that have a bolometric luminosity that is different by a factor of 100, but at the specific wavelength you are interested in they have the same flux, then you will probably want equal numbers of photons for both sources. You can enable this with:

```
m.set_sample_sources_evenly(True)
```

Note that this does not yet cause point sources within *Point source collections* to be evenly sampled. For the purposes of this option, a point source collection counts as a single source.

Outputting physical quantities

It is possible to write out a number of physical arrays for each iteration, or just the last iteration. To do this, you will need to set the parameters in `Models.conf.output`:

```
# Density
m.conf.output.output_density = 'last'

# Density difference (shows where dust was destroyed)
m.conf.output.output_density_diff = 'none'

# Energy absorbed (using pathlengths)
m.conf.output.output_specific_energy = 'last'

# Number of unique photons that passed through the cell
m.conf.output.output_n_photons = 'last'
```

Each value can be set to `all` (output all iterations), `last` (output only after last iteration), or `none` (do not output). The default is to output only the last iteration of `specific_energy`. To find out how to view these values, see Post-processing models

Advanced parameters

There are a number of more advanced parameters to control the radiative transfer, but since they are not essential initially, they are described in the Advanced configuration section.

Once the model is set up, you can write it out to the disk for use with the Fortran radiation transfer code:

```
m.write('example.rtin')
```

See *`write()`* for information about the available options.

3.3.2 Analytical YSO Models

The *Arbitrary Models* class should allow users to set up arbitrary problems. However, the Python module also provides classes that build on top of *Model* that make it easy to specify certain kinds of problems. These classes support all the methods available for the *Model* class, and define new ones. The *AnalyticalYSOModel* makes it easy to set up sources with flared disks, and rotationally flattened envelopes, optionally with bipolar cavities. To use this class, you will first need to import it:

```
from hyperion.model import AnalyticalYSOModel
```

it is then easy to set up such a model using:

```
m = AnalyticalYSOModel()
```

The model can then be set up using methods of the *AnalyticalYSOModel* instance. This is described in more detail in the following section:

Setting up a YSO model

Note: If you haven't already done so, please make sure you read the Important Notes to understand whether to specify dust or dust+gas densities!

Source parameters

The stellar luminosity and radius should be set via the following attributes:

```
m.star.luminosity = 5 * lsun
m.star.radius = 2 * rsun
```

and either the temperature or the spectrum of the source can be set, using:

```
m.star.temperature = 10000.
```

or:

```
m.star.spectrum = (nu, fnu)
```

Flared disks

Flared disks can be added using the *add_flared_disk()* method, and capturing the reference to the *FlaredDisk* object to set the parameters further:

```
disk = m.add_flared_disk()
disk.mass = 0.01 * msun             # Disk mass
disk.rmin = 10 * rsun               # Inner radius
disk.rmax = 300 * au                # Outer radius
disk.r_0 = 100. * au                # Radius at which h_0 is defined
disk.h_0 = 5 * au                   # Disk scaleheight at r_0
disk.p = -1                         # Radial surface density exponent
disk.beta = 1.25                    # Disk flaring power
```

Envelopes

Power-law spherically symmetric envelope The simplest kind of envelope is a spherically symmetric envelope with a power-law distribution in density. A power-law envelope can be added using the *add_power_law_envelope()* method, and capturing the reference to the *PowerLawEnvelope* object to set the parameters further:

```
envelope = m.add_power_law_envelope()
envelope.mass = 0.1 * msun          # Envelope mass
envelope.rmin = au                  # Inner radius
envelope.rmax = 10000 * au          # Outer radius
envelope.power = -2                 # Radial power
```

Ulrich rotationally flattened envelope A more complex envelope density distribution is that of Ulrich (1976), which consists of a rotationally flattened envelope. A power-law envelope can be added using the *add_ulrich_envelope()* method, and capturing the reference to the *UlrichEnvelope* object to set the parameters further:

```
envelope = m.add_ulrich_envelope()
envelope.mdot = 1e-4 * msun / yr    # Infall rate
envelope.rmin = 0.1 * au            # Inner radius
envelope.rc = 100 * au              # Centrifugal radius
envelope.rmax = 1000 * au           # Outer radius
```

As mentioned in the Important Notes, the infall rate `mdot` is not necessarily the dust+gas infall rate - for instance if the dust opacities are per unit dust mass, the infall rate specified should only include the dust (because it is only used to set the density structure, and does not add any accretion luminosity).

Note: the Ulrich (1976) solution is sometimes (incorrectly) referred to as the Terebey, Shu, and Cassen (TSC) solution, which is much more complex. The Ulrich envelope implemented here is the same envelope type as is often implemented in other radiation transfer codes.

Bipolar cavities

Once an envelope has been created, bipolar cavities can be carved out in it by calling the `add_bipolar_cavities` method on the envelope object, which returns a *BipolarCavity* instance:

```
cavity = envelope.add_bipolar_cavities()
cavity.power = 1.5                  # Shape exponent z~w^exp
cavity.r_0 = 1.e-20                 # Radius to specify rho_0 and theta_0
cavity.theta_0 = 10                 # Opening angle at r_0 (degrees)
cavity.rho_0 = 1.e-20               # Density at r_0 in g/cm^3
cavity.rho_exp = 0.                 # Vertical density exponent
```

Ambient medium

In addition to disks and envelopes, it is also possible to add a constant ambient density medium using the *add_ambient_medium()* method, which returns an *AmbientMedium* instance:

```
ambient = m.add_ambient_medium()
ambient.rmin = 0.1 * au             # Inner radius
ambient.rmax = 1000 * au            # Outer radius
ambient.rho = 1.e-20                # Ambient density in g/cm^3
```

By default, the ambient medium simply adds a constant density to any pre-existing density. However, in some cases you may want to use this as a minimum density. In order to do this, set the `subtract` attribute to a list containing any component you want to subtract from the constant density:

```
disk = m.add_flared_disk()
...
envelope = m.add_ulrich_envelope()
...
ambient = m.add_ambient_medium()
...
ambient.subtract = [envelope, disk]
```

In regions where the sum of the densities from these components exceeds the ambient density, no dust is added to the model, whereas in regions where the sum of the density of the components is below the ambient density, the density gets set to the ambient density.

Accretion

Viscous dissipation

Note: This feature is still experimental, please use with caution and report any issues!

To simulate the effects of accretion due to viscous dissipation of energy in the disk, you can use an 'alpha accretion' disk instead of a plain flared disk. Such disks can be added using the *`add_alpha_disk()`* method, and capturing the reference to the *`AlphaDisk`* object to set the parameters further. The parameters are the same as for flared disks:

```
disk = m.add_alpha_disk()
disk.mass = 0.01 * msun             # Disk mass
disk.rmin = 10 * rsun               # Inner radius
disk.rmax = 300 * au                # Outer radius
disk.r_0 = 100. * au                # Radius at which h_0 is defined
disk.h_0 = 5 * au                   # Disk scaleheight at r_0
disk.p = -1                         # Radial surface density exponent
disk.beta = 1.25                    # Disk flaring power
```

except that the accretion properties of the disk can also be specified. Either the disk accretion rate can be specified:

```
disk.mdot = 1e-6 * msun / yr        # Disk accretion rate
```

or the accretion luminosity from viscous dissipation:

```
disk.lvisc = 0.01 * lsun
```

As mentioned in the Important Notes, the disk accretion rate `mdot` should always be the total dust+gas accretion rate, because it is the total dust+gas accretion rate that sets the accretion luminosity.

Note that this accretion luminosity only includes the luminosity down to `disk.rmin`, and does not include the luminosity from the stellar surface (see *Magnetospheric accretion*). For more details on the accretion luminosity from viscous dissipation, see *`AlphaDisk`*.

Magnetospheric accretion

Note: This feature is still experimental, please use with caution and report any issues!

Another important component of the accretion luminosity is that from the dissipation of energy as matter accretes onto the central star from the inner edge of the gas disk. In a simplistic model of magnetospheric accretion, matter free-falls from the radius at which the disk is truncated by the magnetosphere to the surface of the star. Half the energy goes into X-rays, and half goes into heating spots on the stellar surface, and is then re-emitted with a spectrum hotter than the rest of the stellar surface.

To help set this up, a convenience method *setup_magnetospheric_accretion()* is provided, which takes the accretion rate, the radius at which the matter free-falls from, the spot covering fraction, and optionally parameters describing the X-ray spectrum. For example:

```
m.setup_magnetospheric_accretion(1.e-6 * msun / yr, 5 * m.star.radius, 0.2)
```

will set up an X-ray and a hot spot emission component from the central source. The method does not currently set up actual spots, it assumes that the spots cover the star uniformly, and the spot covering fraction determines the temperature of the hot spots (a smaller covering fraction results in a larger hot spot temperature for a fixed accretion rate).

See *setup_magnetospheric_accretion()* for more details.

Dust

The dust file to use for each component should be specified using the `dust` attribute for the component, e.g.:

```
disk.dust = 'www003.hdf5'
envelope.dust = 'kmh.hdf5'
cavity.dust = 'kmh_hdf5'
```

The dust can be specified either as a filename or an instance of one of the dust types.

Grid

The gridding of the density can done automatically, but you will need to specify a grid size. Either a spherical polar or cylindrical polar grid can be used. To use the spherical polar grid:

```
m.set_spherical_polar_grid_auto(n_r, n_theta, n_phi)
```

and to use the cylindrical polar grid:

```
m.set_cylindrical_polar_grid_auto(n_w, n_z, n_phi)
```

The grid is set up in such a way as to provide very fine resolution at the inner edge of the disk or envelope, and logarithmic spacing of cell walls on large scales.

In some cases, this automated gridding may not be appropriate, and you may want to specify the grid geometry yourself, for example if you have other sources of emission than the one in the center. In this case, the *set_spherical_polar_grid()* and *set_cylindrical_polar_grid()* methods described in Coordinate grids and physical quantities can be used. As a reminder, these take the position of the walls as arguments rather than the number of cells, e.g.:

```
r = np.logspace(np.log10(rsun), np.log10(100 * au), 400)
r = np.hstack([0., r])  # add cell wall at r=0
theta = np.linspace(0., pi, 201)
phi = np.array([0., 2 * pi])
m.set_spherical_polar_grid(r, theta, phi)
```

Optically thin temperature radius

When setting up the disk or envelope inner/outer radii, it can sometimes be useful to set it to a 'dynamic' quantity such as the sublimation radius of dust. A convenience class is available for this purpose:

```
from hyperion.util.convenience import OptThinRadius
```

The `OptThinRadius` class allows you to simply specify a temperature T_d, and when preparing the model, the code will pick the radius at which the temperature would be equal to the value specified if the dust was optically thin:

$$r = r_\star \left\{ 1 - \left[1 - 2 \frac{T_d^4}{T_{\rm eff}^4} \frac{\kappa_{\rm plank}(T_d)}{\kappa_\star} \right]^2 \right\}^{-1/2}$$

where $T_{{\rm eff},\star}$ is the effective temperature of the central source, and $\kappa_{\star)}$ is the mean opacity to a radiation field with the spectrum of the central source. In practice, you can use this as follows:

```
disk = m.add_flared_disk()
disk.mass = 0.01 * msun
disk.rmin = OptThinRadius(1600.)
disk.rmax = 300. * au
...
```

and the inner disk radius will be set to the radius at which the optically thin temperature would have fallen to 1600K, emulating dust sublimation.

To set up the dust, images, and configuration, see the Preparing dust properties, Setting up images and SEDs, and Radiative transfer settings sections of the Arbitrary Models description.

Once the model is set up, you can write it out to the disk for use with the Fortran radiation transfer code:

```
m.write('example.rtin')
```

See *`write()`* for information about the available options.

Note: One of the available options is `merge_if_possible=`, which if set to `True` will merge the various density components into a single one if the dust types match. This allows the code to run faster, but on the other hand means that if tracking e.g. photon origin, the separate origin of components that have been merged will be lost. This option is enabled by default, but you may want to disable it.

And the following pages give details and advice on particular configuration settings:

3.3.3 Choosing the number of photons wisely

Note: This section is incomplete at this time, and only covers choosing the photon numbers for the specific energy/temperature calculation.

As described in Radiative transfer settings and Advanced configuration, the number of photons should be set with the:

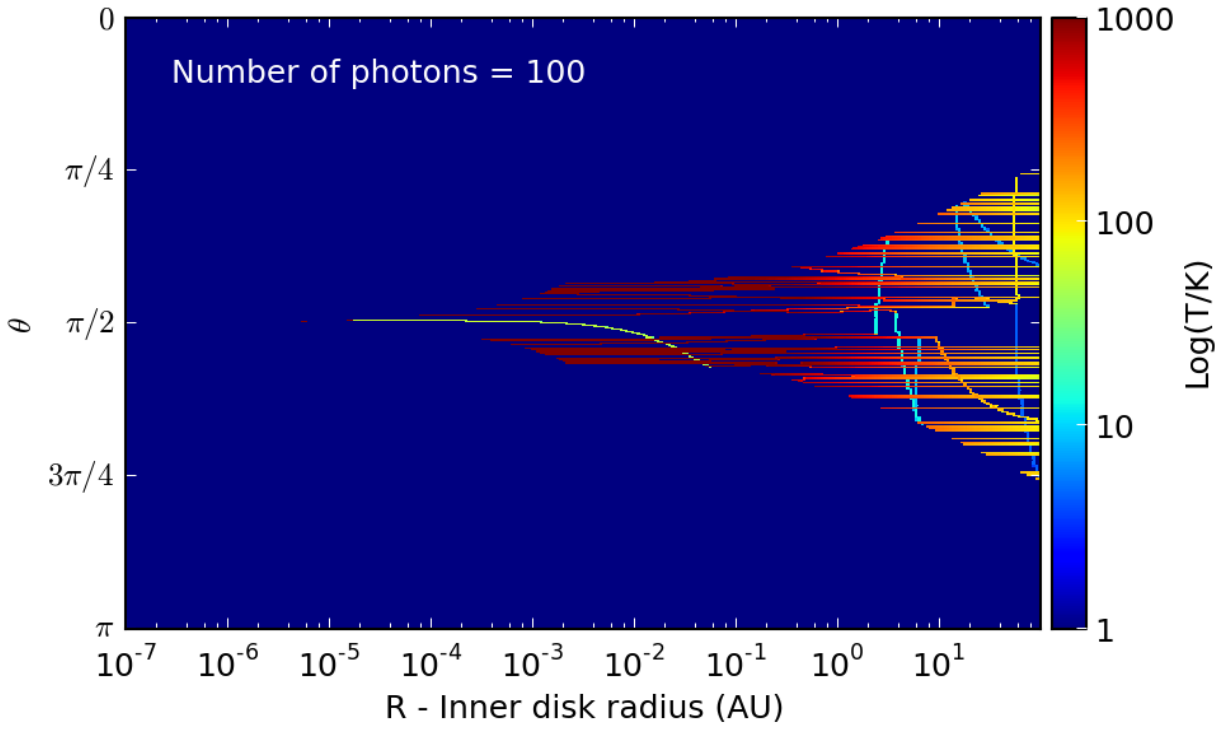
```
m.set_n_photons(...)
```

method. The arguments to specify depend on the type of calculation

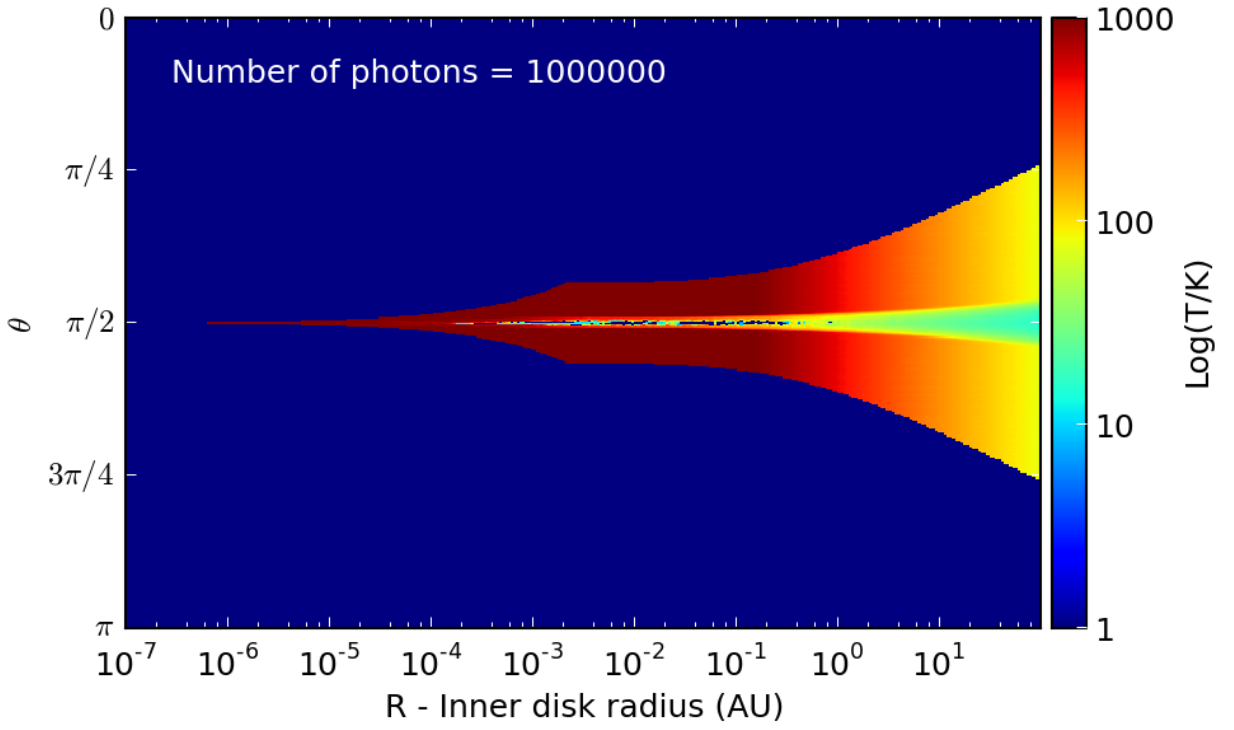
Specific Energy/Temperature

The number of photons used in the initial specific energy calculation is set with the `initial=` keyword argument. A good starting value for this if the density grid is close to optically thin is to set it to be at least the number of cells in the grid. If the optical depth is much larger, e.g. in the case of protoplanetary disks, one may need to choose 10 or 100 times the number of cells in order to get a good signal-to-noise.

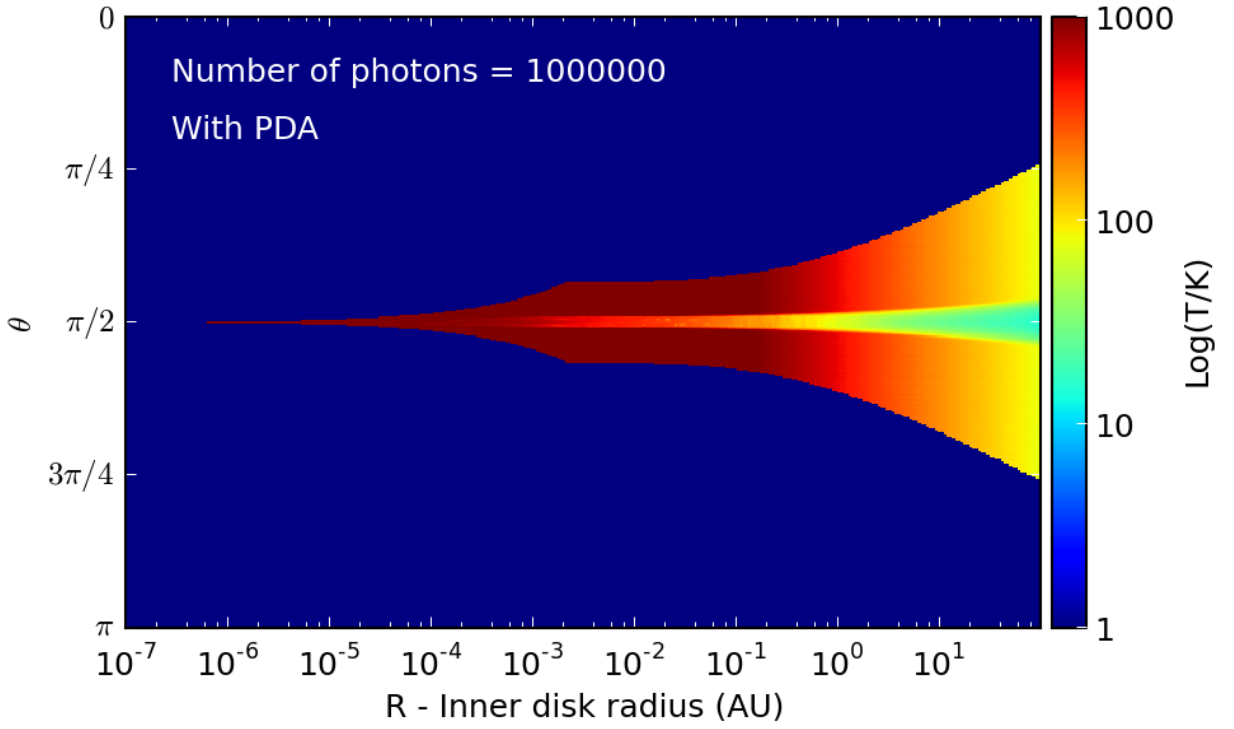
The best way to check whether an adequate value has been chosen is to extract the specific energy or temperature grids as described in Extracting physical quantities, and to visualize these. The following image shows an example of the specific energy in an azimuthally symmetric cylindrical grid (i.e. showing z vs r) where the initial number of photons is too low. Individual photon propagation paths can be seen, and the temperature map is very poorly defined.



If the temperature is increased, then the temperature map becomes smoother, though in the densest regions, the temperature is still very noisy:



Once it is not possible to realistically increase the number of photons without running into computational limitations, one can instead resort to using the PDA approximation (described in *Diffusion*) to compute the missing temperature values in the most optically thick regions.



Note: it is possible to write model input files yourself directly in HDF5 and bypass the Python library entirely (but

this is reserved for advanced users!). See Model Input HDF5 Format for more information.

3.4 Running models

3.4.1 Using the *hyperion* command-line wrapper

Once an .rtin file has been created (see Setting up models), the model can be run using the compiled Fortran code. Note that the model can be run on a different computer/cluster to the computer on which is was set up, because the `.rtin` files are portable.

The easiest way to run a model is to invoke the `hyperion` command-line utility, specifying the input and output file (we use the `.rtout` extensions for output files):

```
hyperion model.rtin model.rtout
```

Note: `hyperion` is a command-line Python wrapper around the Fortran binaries that gets installed with the Python Hyperion library.

To run Hyperion in parallel, you can use:

```
hyperion -m <n_processes> model.rtin model.rtout
```

where `<n_processes>` is the number of processes to run in parallel (does not need to equal the number of cores in the computer or cluster). For example, to run the code over 24 processes, you can use:

```
hyperion -m 24 model.rtin model.rtout
```

This may not work with all MPI installations. If you have issues, see the next section on calling the Fortran binaries directly (and report the issue).

3.4.2 Calling the Fortran binaries directly

`hyperion` is in fact a wrapper to grid specific binaries:

- `hyperion_car` and `hyperion_car_mpi` for cartesian grids
- `hyperion_cyl` and `hyperion_cyl_mpi` for cylindrical polar grids
- `hyperion_sph` and `hyperion_sph_mpi` for spherical polar grids
- `hyperion_amr` and `hyperion_amr_mpi` for AMR grids
- `hyperion_oct` and `hyperion_oct_mpi` for Oct-tree grids

These binaries can be called directly instead of the `hyperion` wrapper. For example, to run a model with a cartesian grid in serial, you would use:

```
hyperion_car model.rtin model.rtout
```

To use the parallel version of the code, use the relevant binary, with the `_mpi` suffix appended, and launch it using the command relevant to your MPI installation, for example:

```
mpirun -n 128 hyperion_car_mpi model.rtin model.rtout
```

This can also be `mpiexec` or `openmpirun` or `openmpiexec` depending on your MPI installation.

3.4.3 Running the model from the Python scripts

It is also possible to run the serial version of the code directly from the set-up script, by doing:

```
m = Model()
...
m.write('model.rtin')
m.run('model.rtout')
```

To run in parallel, simply do:

```
m.run('model.rtout', mpi=True, n_processes=<n_processes>)
```

As for the `hyperion` command-line wrapper, this may not work with all MPI installations.

3.4.4 Overwriting existing output

By default, if the output file already exists, a confirmation message is shown:

```
WARNING: File exists:  test.rtout
The following command will be run:  rm test.rtout
Do you wish to continue? (y/n)
```

However, this is not always desirable (for example when submitting jobs to clusters). To overwrite an existing output file, then use the `-f` option when calling `hyperion` or on of the `hyperion_*` commands:

```
$ hyperion -f input output
```

of use the `overwrite=True` argument when using `Model.run`:

```
m.run('model.rtout', overwrite=True)
```

3.5 Post-processing models

You've successfully set up and run your model, but now you want to extract the results and do something useful with them. The following sections describe how to retrieve observables (SEDs and images) and quantities (such as density and temperature).

3.5.1 Extracting SEDs and Images

The first step to extracting SEDs and images from the models is to create an instance of the `ModelOutput` class, giving it the name of the output file:

```
from hyperion.model import ModelOutput
m = ModelOutput('simple_model.rtout')
```

SEDs

To extract SEDs, use the *`get_sed()`* method:

```
sed = m.get_sed()
```

A number of arguments can be passed to *get_sed()*, for example to select specific Stokes parameters, inclinations, apertures, to scale the SED to a specific distance, to convert it to certain units, to extract the SED originating from different components, etc. For full details about the available arguments, see the *get_sed()* documentation. The method returns a single *SED* object that contains e.g. the wavelengths (`sed.wav`), frequencies (`sed.nu`), values (i.e. fluxes, flux densities, or polarization values; `sed.val`), and optionally uncertainties (`sed.unc`). See *SED* for the full list of the available attributes.

By default, the I stokes parameter is returned for all inclinations and apertures, and `sed.val` is a data cube with three dimensions (inclinations, apertures, and wavelengths respectively). If an aperture or an inclination is specified, that dimension is removed from the array. Thus, specifying both inclination and aperture makes `sed.val` a one-dimensional array.

The default units are microns for `sed.wav` and ergs/s for `sed.val`. If a distance is specified when extracting the SED, `sed.val` is in ergs/cm^2/s by default.

If uncertainties are requested, then `sed.unc` is set, which is uncertainty array with the same dimensions and units as `sed.val`:

```
sed = m.get_sed(uncertainties=True)
```

See Plotting and writing out SEDs for an example of extracting SEDs from a model.

Images

To extract images, use the *get_image()* method:

```
image = m.get_image()
```

Similarly to SEDs, a number of arguments can be passed to *get_image()*. For full details about the available arguments, see the *get_image()* documentation. This method returns a single *Image* object that contains e.g. the wavelengths (`image.wav`), frequencies (`image.nu`), values (i.e. fluxes, flux densities, or polarization values; `image.val`), and optionally uncertainties (`image.unc`). See *Image* for the full list of the available attributes.

As for SEDs, the attributes of the image will depend on the options specified. The main difference compared to SEDs is that there are two dimensions for the x and y position in the image instead of the aperture dimension.

See Plotting and writing images for an example of extracting images from a model.

3.5.2 Extracting physical quantities

As described in Radiative transfer settings, it is possible to specify which gridded physical quantities should be output after the radiative transfer. For example, by default, the values of the specific energy absorbed in each cell are output, and this can be used to determine the temperature in each cell.

To access these gridded physical quantities, first access the model output file with:

```
from hyperion.model import ModelOutput
m = ModelOutput('output_file.rtout')
```

then make use of the `get_quantities` method to extract a grid object:

```
grid = m.get_quantities()
```

By default, this will extract the physical quantities from the last iteration, but it is also possible to extract quantities from previous iterations, e.g.:

```
grid = m.get_quantities(iteration=1)
```

The value of `iteration` should be zero-based, so `1` indicates the second iteration.

The `grid` variable now contains both the geometrical information about the grid, and the quantities output in the iteration specified. How this information is accessed depends on the grid type, as described below.

Regular 3-d grids

For regular 3-d grids, the position of the center of the cells can be accessed with the `x`, `y`, and `z` attributes for cartesian grids, the `w`, `z`, and `p` attributes for cylindrical polar grids, and the `r`, `t`, and `p` attributes for spherical polar grids. These are 1-d arrays, but it is also possible to retrieve 3-d versions of these arrays by adding `g` in front, e.g. `gx`, `gy`, and `gz`. It is also possible to retrieve the original wall positions by adding the `_wall` suffix to the 1-d array names, e.g. `x_wall`, `y_wall`, and `z_wall`.

The physical quantities are stored in a dictionary called `quantities`, where each element in the dictionary is a quantity, and each quantity is stored as a list with as many elements as dust types. Each element is a 3-d Numpy array. Therefore, you can access for example the `specific_energy` values for the first dust type with:

```
values = g.quantities['specific_energy'][0]
```

However, it is also possible to access this with a more convenient notation:

```
values = g['specific_energy'][0].array
```

Although the temperature values are not ever directly present in the output file, if the specific energy values are present, `get_quantities` will automatically calculate and make available the `temperature` quantity which can be accessed as above with:

```
values = g['temperature'][0].array
```

In Visualizing physical quantities for regular 3-d grids, we show how to visualize this information.

AMR grids

When extracting an AMR grid using `get_quantities()`, an `AMRGrid` object is returned. This object contains an attribute named `levels` that is a list of `Level` objects. Each `Level` object contains a `grids` attribute that is a list of `Grid` objects, which in turn have attributes `xmin`, `xmax`, `ymin`, `ymax`, `zmin`, `zmax`, `nx`, `ny`, and `nz` which give the boundaries and number of cells in each direction in the grid (this format is described in more detail in AMR Grids).

Since this is not easy to visualize, Hyperion includes an interface to the yt package for AMR grids. If you extracted the quantities with:

```
amr = m.get_quantities()
```

you can call the following method to output a `StreamStaticOutput` yt object that can be directly used for plotting in yt:

```
pf = amr.to_yt()
```

where `pf` is a yt `StaticOutput` object. See Visualizing physical quantities from adaptive grids with yt for more details and a plotting tutorial.

Octree grids

When extracting an Octree grid using `get_quantities()`, an `OctreeGrid` object is returned. The format of this object is described in detail in Octree Grids.

As for AMR grids, Hyperion includes an interface to the yt package for Octree grids. If you extracted the quantities with:

```
oct = m.get_quantities()
```

you can call the following method to output a `StreamStaticOutput` yt object that can be directly used for plotting in yt:

```
pf = oct.to_yt()
```

where `pf` is a yt `StaticOutput` object. See Visualizing physical quantities from adaptive grids with yt for more details and a plotting tutorial.

The Tutorials section contains a number of examples illustrating how to extract and visualize observables and quantities.

Note: A convenience script is provided to quickly extract image cubes and physical grids for inspection as FITS files:

```
# Retrieve all images
hyperion2fits --images model.rtout

# Retrieve all physical arrays (only works for regular grids)
hyperion2fits --physics model.rtout
```

Ds9 version 7 or later is required to be able to navigate FITS cubes with more than 3 dimensions. This is only meant as a quick look tool. To extract properly scaled and sliced information from the output file, see the sections above.

3.6 Tutorials

3.6.1 Basic Python

If you are not comfortable with writing out files or making plots in Python, the following two sections will help you get started:

Writing files in Python

Pure Python

The most basic way to write files in Python is to simply open a file with write access:

```
f = open('file.txt', 'wb')
```

and to then call the `write` method to write to the file:

```
f.write("Hello World")
```

Line returns have to be explicitly included using `\n`:

```
f.write("Line 1\n")
f.write("line 2\n")
```

And files should be closed with:

```
f.close()
```

The best way to write out variables with this technique is to use string formatting which is described in more detail here. The basic command to format variables into a string is:

```
format % variables
```

where `format` is a string containing the format statements and variables is a tuple of the values, for example:

```
>>> print "%s %5.2f %10.4e" % ("name", 3.4, 1.e-10)
name  3.40 1.0000e-10
```

We can use this when writing out files, so if we have two lists or arrays of values `a` and `b` we can do:

```
a = [1,2,3,4,5]
b = [2,6,4,3,2]

f = open('file.txt', 'wb')
for i in range(len(a)):
    f.write("%i %5.2f\n" % (a[i], b[i]))
f.close()
```

which will produce a file containing:

```
1  2.00
2  6.00
3  4.00
4  3.00
5  2.00
```

Numpy

Numpy provides a function called `savetxt` that makes it easy to write out arrays to files. Given two lists or arrays `a` and `b` as above, one can simply do:

```
import numpy as np
a = [1,2,3,4,5]
b = [2,6,4,3,2]
np.savetxt('file_numpy.txt', zip(a, b), fmt="%i %5.2f")
```

which produces exactly the same output as above and avoids the for loop.

An introduction to Matplotlib

Before we start plotting SEDs and images, let's see how Matplotlib works. The first thing we want to do is to import Matplotlib:

```
import matplotlib.pyplot as plt
```

In general, if you are plotting from a script as opposed to interactively, you probably don't want each figure to pop up to the screen before being written out to a file. In that case, use:

```
import matplotlib as mpl
mpl.use('Agg')
import matplotlib.pyplot as plt
```

This sets the default backend for plotting to `Agg`, which is a non-interactive backend.

We now want to create a figure, which we do using:

```
fig = plt.figure()
```

This creates a new figure, which we can now access via the `fig` variable (`fig` is just the variable name we chose, you can use anything you want). The figure is just the container for anything you are going to plot, so we next need to add a set of axes. The simplest way to do this is:

```
ax = fig.add_subplot(1,1,1)
```

The arguments for `add_subplot` are the number of subplots in the x and y direction, followed by the index of the current one.

The most basic command you can now type is `plot`, which draws a line plot. The basic arguments are the x and y coordinates of the vertices:

```
ax.plot([1,2,3,4],[2,3,2,1])
```

Now we can simply save the plot to a figure. A number of file types are supported, including PNG, JPG, EPS, and PDF. Let's write our masterpiece out to a PNG file:

```
fig.savefig('line_plot.png')
```

Note: If you are using a Mac, then writing out in PNG while you are working on the plot is a good idea, because if you open it in Preview.app, it will update automatically whenever you run the script (you just need to click on the plot window to make it update). When you are happy with your plot, you can always switch to EPS.

Our script now looks like:

```
import matplotlib as mpl
mpl.use('Agg')
import matplotlib.pyplot as plt

fig = plt.figure()
ax = fig.add_subplot(1,1,1)
ax.plot([1,2,3,4],[2,3,2,1])
fig.savefig('line_plot.png')
```

3.6.2 Post-processing

Plotting and writing out SEDs

So you've run a model with SEDs, and you now want to plot them or write the out to files. The plotting library used in this tutorial is Matplotlib but there is no reason why you can't use another. The examples below get you to write Python scripts, but you can also run these interactively in python or ipython if you like.

Example model

As an example, let's set up a simple model of a star with a blackbody spectrum surrounded by a flared disk using the *AnalyticalYSOModel* class.

```
import numpy as np

from hyperion.model import AnalyticalYSOModel
from hyperion.util.constants import rsun, au, msun, sigma

# Initalize the model
```

```
m = AnalyticalYSOModel()

# Set the stellar parameters
m.star.radius = 2. * rsun
m.star.temperature = 4000.
m.star.luminosity = 4 * (2. * rsun) ** 2 * sigma * 4000 ** 4

# Add a flared disk
disk = m.add_flared_disk()
disk.mass = 0.01 * msun
disk.rmin = 10 * m.star.radius
disk.rmax = 200 * au
disk.r_0 = m.star.radius
disk.h_0 = 0.01 * disk.r_0
disk.p = -1.0
disk.beta = 1.25
disk.dust = 'kmh_lite.hdf5'

# Use raytracing to improve s/n of thermal/source emission
m.set_raytracing(True)

# Use the modified random walk
m.set_mrw(True, gamma=2.)

# Set up grid
m.set_spherical_polar_grid_auto(399, 199, 1)

# Set up SED for 10 viewing angles
sed = m.add_peeled_images(sed=True, image=False)
sed.set_viewing_angles(np.linspace(0., 90., 10), np.repeat(45., 10))
sed.set_wavelength_range(150, 0.02, 2000.)
sed.set_track_origin('basic')

# Set number of photons
m.set_n_photons(initial=1e5, imaging=1e6,
                raytracing_sources=1e4, raytracing_dust=1e6)

# Set number of temperature iterations
m.set_n_initial_iterations(5)

# Write out file
m.write('class2_sed.rtin')
m.run('class2_sed.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

Note that the subsequent plotting code applies to any model, not just *AnalyticalYSOModel* models.

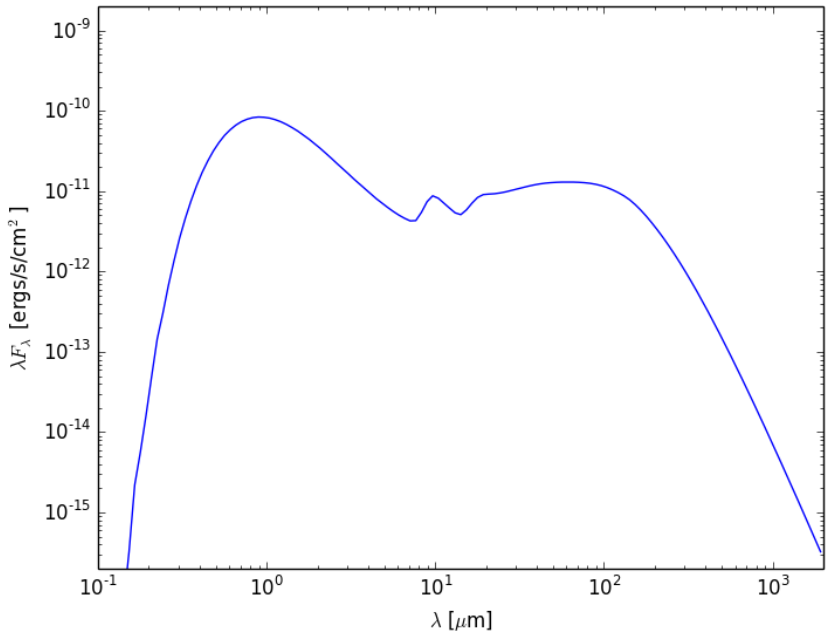
Plotting SEDs

Note: If you have never used Matplotlib before, you can first take a look at the An introduction to Matplotlib tutorial.

Total flux Once the above model has run, we are ready to make a simple SED plot. The first step is to extract the SED from the output file from the radiation transfer code. This step is described in detail in *Post-processing models*. Combining this with what we learned above about making plots, we can write scripts that will fetch SEDs and plot them. For example, if we want to plot an SED for the first inclination and the largest aperture, we can do:

```
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Open the model
m = ModelOutput('class2_sed.rtout')

# Create the plot
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)

# Extract the SED for the smallest inclination and largest aperture, and
# scale to 300pc. In Python, negative indices can be used for lists and
# arrays, and indicate the position from the end. So to get the SED in the
# largest aperture, we set aperture=-1.
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc)

# Plot the SED. The loglog command is similar to plot, but automatically
# sets the x and y axes to be on a log scale.
ax.loglog(sed.wav, sed.val)

# Add some axis labels (we are using LaTeX here)
ax.set_xlabel(r'$\lambda$ [$\mu$m]')
ax.set_ylabel(r'$\lambda F_\lambda$ [ergs/s/cm$^2$]')

# Set view limits
ax.set_xlim(0.1, 2000.)
ax.set_ylim(2.e-16, 2.e-9)

# Write out the plot
fig.savefig('class2_sed_plot_single.png')
```

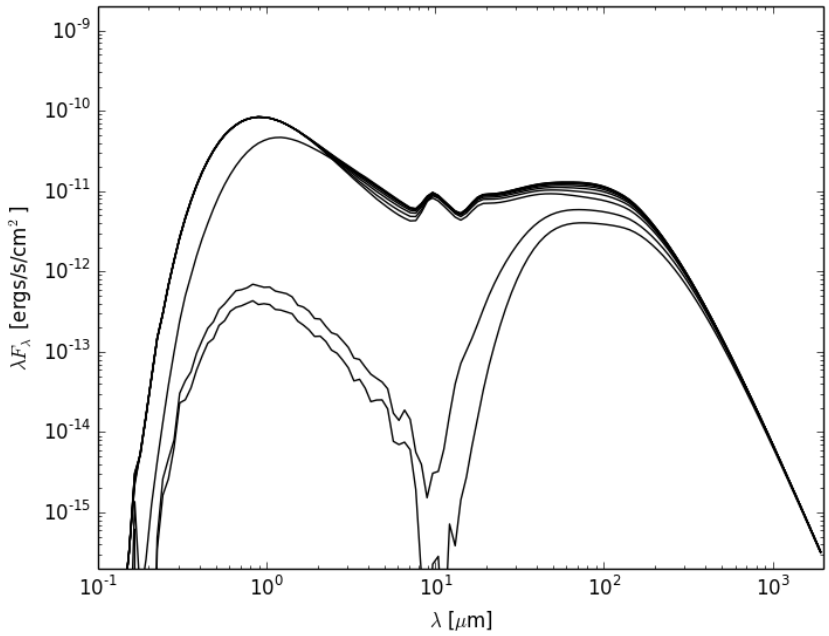
This script produces the following plot:



Now let's say that we want to plot the SED for all inclinations. We can either call *get_sed()* and loglog once for each inclination, or call it once with `inclination='all'` and then call only loglog once for each inclination:

```
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

m = ModelOutput('class2_sed.rtout')

fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)

# Extract all SEDs
sed = m.get_sed(inclination='all', aperture=-1, distance=300 * pc)

# Plot SED for each inclination
for i in range(sed.val.shape[0]):
    ax.loglog(sed.wav, sed.val[i, :], color='black')

ax.set_xlabel(r'$\lambda$ [$\mu$m]')
ax.set_ylabel(r'$\lambda F_\lambda$ [ergs/s/cm$^2$]')
ax.set_xlim(0.1, 2000.)
ax.set_ylim(2.e-16, 2.e-9)
fig.savefig('class2_sed_plot_incl.png')
```

This script produces the following plot:



Individual SED components Now let's do something a little more fancy. Assuming that you set up the SEDs with photon tracking:

```
sed.set_track_origin('basic')
```

or:

```
sed.set_track_origin('detailed')
```

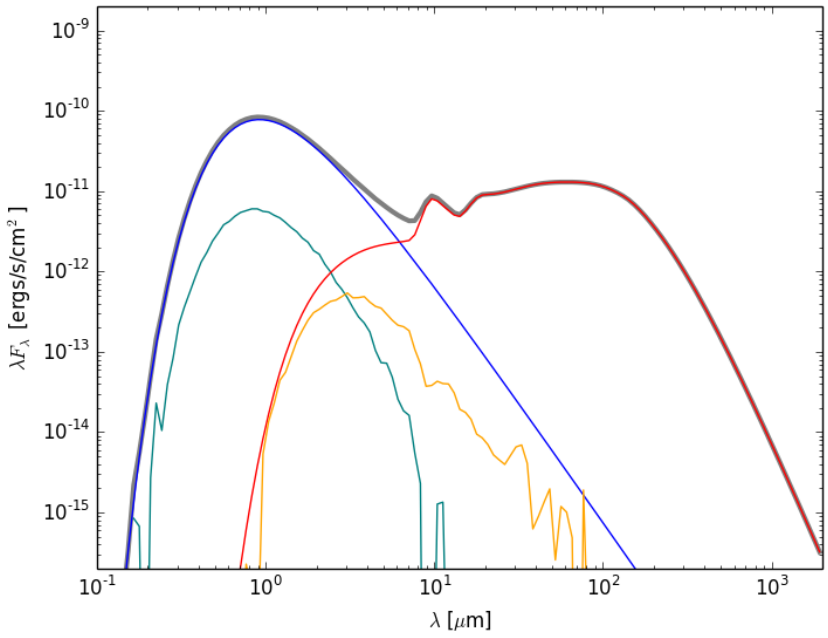
you can plot the individual components. Notice that we included the former in the model at the top of this page, so we can make use of it here to plot separate components of the SED.

The following example retrieves each separate components, and plots it in a different color:

```
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

m = ModelOutput('class2_sed.rtout')

fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)

# Total SED
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc)
ax.loglog(sed.wav, sed.val, color='black', lw=3, alpha=0.5)

# Direct stellar photons
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc,
                component='source_emit')
ax.loglog(sed.wav, sed.val, color='blue')

# Scattered stellar photons
```

```
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc,
                        component='source_scat')
ax.loglog(sed.wav, sed.val, color='teal')

# Direct dust photons
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc,
                        component='dust_emit')
ax.loglog(sed.wav, sed.val, color='red')

# Scattered dust photons
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc,
                        component='dust_scat')
ax.loglog(sed.wav, sed.val, color='orange')


ax.set_xlabel(r'$\lambda$ [$\mu$m]')
ax.set_ylabel(r'$\lambda F_\lambda$ [ergs/s/cm$^2$]')
ax.set_xlim(0.1, 2000.)
ax.set_ylim(2.e-16, 2.e-9)
fig.savefig('class2_sed_plot_components.png')
```

This script produces the following plot:



Writing out SEDs

Note: If you have never written text files from Python before, you can first take a look at the Writing files in Python tutorial.

The output files from the radiative transfer code are in the HDF5 file format, and can therefore be accessed directly from most programming/scripting languages. However, in many cases it might be most convenient to write a small Python script to extract the required information and to write it out to files that can then be read in to other tools.

For instance, you may want to write out the SEDs to ASCII files. To do this, the first step, as for plotting (see *Plotting SEDs* above) is to extract the SED from the output file from the radiation transfer code. This step is also described in detail in *Post-processing models*. Once we have extracted an SED we can write a script that will write it out to disk. For example, if we want to write out the SED for the first inclination and the largest aperture from the *Example Model*, we can do:

```
import numpy as np

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

m = ModelOutput('class2_sed.rtout')
sed = m.get_sed(inclination=0, aperture=-1, distance=300 * pc)
np.savetxt('sed.txt', list(zip(sed.wav, sed.val)), fmt="%11.4e %11.4e")
```

This script produces a file that looks like:

```
 1.9247e+03  3.2492e-16
 1.7825e+03  4.6943e-16
 1.6508e+03  6.7731e-16
 1.5288e+03  9.7580e-16
 1.4159e+03  1.4036e-15
 1.3113e+03  2.0154e-15
 1.2144e+03  2.8884e-15
 1.1247e+03  4.1310e-15
...
```

Plotting and writing images

As mentioned in Plotting and writing out SEDs, the output files from the radiative transfer code are in the HDF5 file format, and can therefore be accessed directly from most programming/scripting languages. However, in most cases it is easiest to use the Hyperion Python library to extract the required information and write it out to files. In this tutorial, we learn how to write out images to FITS files (for an example of writing out SEDs, see Plotting and writing out SEDs).

Example model

In this example, we set up a simple model that consists of a cube of constant density, with a point source shining isotropically. A denser cube then causes some of the emission to be blocked, and casts a shadow:

```
import numpy as np

from hyperion.model import Model
from hyperion.util.constants import pc, lsun

# Initialize model
m = Model()

# Set up 64x64x64 cartesian grid
w = np.linspace(-pc, pc, 64)
m.set_cartesian_grid(w, w, w)

# Add density grid with constant density and add a higher density cube inside to
# cause a shadow.
density = np.ones(m.grid.shape) * 1e-21
density[26:38, 26:38, 26:38] = 1.e-18
```

```
m.add_density_grid(density, 'kmh_lite.hdf5')

# Add a point source in the center
s = m.add_point_source()
s.position = (0.4 * pc, 0., 0.)
s.luminosity = 1000 * lsun
s.temperature = 6000.

# Add multi-wavelength image for a single viewing angle
image = m.add_peeled_images(sed=False, image=True)
image.set_wavelength_range(20, 1., 1000.)
image.set_viewing_angles([60.], [80.])
image.set_image_size(400, 400)
image.set_image_limits(-1.5 * pc, 1.5 * pc, -1.5 * pc, 1.5 * pc)

# Set runtime parameters
m.set_n_initial_iterations(5)
m.set_raytracing(True)
m.set_n_photons(initial=4e6, imaging=4e7,
                raytracing_sources=1, raytracing_dust=1e7)

# Write out input file
m.write('simple_cube.rtin')
m.run('simple_cube.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

Plotting images

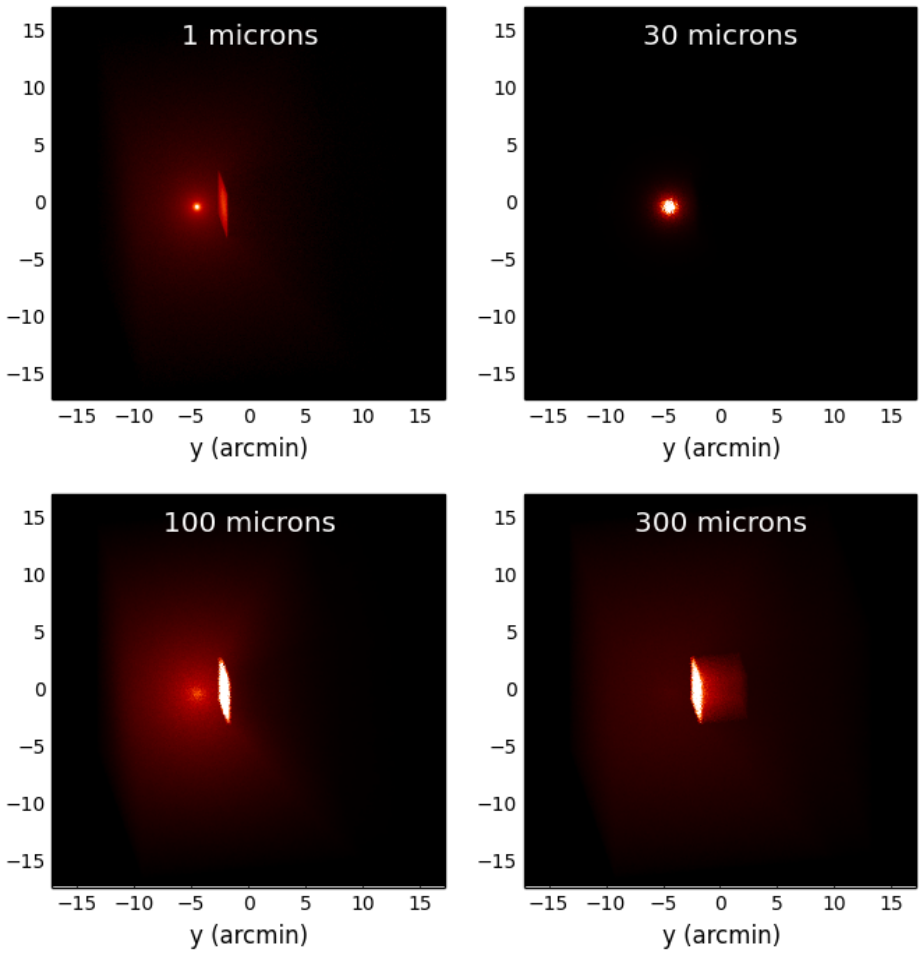
Note: If you have never used Matplotlib before, you can first take a look at the An introduction to Matplotlib tutorial.

The first step is to extract the image cube from the output file (`simple_cube.rtout`). This step is described in detail in *Post-processing models*. We can make a plot of the surface brightness

```
import numpy as np
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Open the model
m = ModelOutput('simple_cube.rtout')

# Extract the image for the first inclination, and scale to 300pc. We
# have to specify group=1 as there is no image in group 0.
image = m.get_image(inclination=0, distance=300 * pc, units='MJy/sr')

# Open figure and create axes
fig = plt.figure(figsize=(8, 8))

# Pre-set maximum for colorscales
VMAX = {}
VMAX[1] = 10.
VMAX[30] = 100.
```

```
VMAX[100] = 2000.
VMAX[300] = 2000.

# We will now show four sub-plots, each one for a different wavelength
for i, wav in enumerate([1, 30, 100, 300]):

    ax = fig.add_subplot(2, 2, i + 1)

    # Find the closest wavelength
    iwav = np.argmin(np.abs(wav - image.wav))

    # Calculate the image width in arcseconds given the distance used above
    w = np.degrees((1.5 * pc) / image.distance) * 60.

    # This is the command to show the image. The parameters vmin and vmax are
    # the min and max levels for the colorscale (remove for default values).
    ax.imshow(np.sqrt(image.val[:, :, iwav]), vmin=0, vmax=np.sqrt(VMAX[wav]),
              cmap=plt.cm.gist_heat, origin='lower', extent=[-w, w, -w, w])

    # Finalize the plot
    ax.tick_params(axis='both', which='major', labelsize=10)
    ax.set_xlabel('x (arcmin)')
    ax.set_ylabel('y (arcmin)')
    ax.set_title(str(wav) + ' microns', y=0.88, x=0.5, color='white')

fig.savefig('simple_cube_plot.png', bbox_inches='tight')
```

This script produces the following plot:



Writing out images

Writing out images to text files does not make much sense, so in this section we see how to write out images extracted from the radiative transfer code results to a FITS file, and add WCS information. Once a 2D image or 3D wavelength cube have been extracted as shown in *Plotting images*, we can write them out to a FITS file using Astropy:

```
from astropy.io import fits

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Retrieve image cube as before
m = ModelOutput('simple_cube.rtout')
image = m.get_image(inclination=0, distance=300 * pc, units='MJy/sr')

# The image extracted above is a 3D array. We can write it out to FITS.
# We need to swap some of the directions around so as to be able to use
# the ds9 slider to change the wavelength of the image.
fits.writeto('simple_cube.fits', image.val.swapaxes(0, 2).swapaxes(1, 2),
             clobber=True)

# We can also just output one of the wavelengths
fits.writeto('simple_cube_slice.fits', image.val[:, :, 1], clobber=True)
```

Writing out images with WCS information

Adding World Coordinate System (WCS) information is easy using Astropy:

```
import numpy as np

from astropy.io import fits
from astropy.wcs import WCS

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Retrieve image cube as before
m = ModelOutput('simple_cube.rtout')
image = m.get_image(inclination=0, distance=300 * pc, units='MJy/sr')

# Initialize WCS information
wcs = WCS(naxis=2)

# Use the center of the image as projection center
wcs.wcs.crpix = [image.val.shape[1] / 2. + 0.5,
                 image.val.shape[0] / 2. + 0.5]

# Set the coordinates of the image center
wcs.wcs.crval = [233.4452, 1.2233]

# Set the pixel scale (in deg/pix)
scale = np.degrees(3. * pc / image.val.shape[0] / image.distance)
wcs.wcs.cdelt = [-scale, scale]

# Set the coordinate system
wcs.wcs.ctype = ['GLON-CAR', 'GLAT-CAR']

# And produce a FITS header
header = wcs.to_header()

# We can also just output one of the wavelengths
fits.writeto('simple_cube_slice_wcs.fits', image.val[:, :, 1],
             header=header, clobber=True)
```

Making 3-color images

Making 3-color images is possible using the Python Imaging Library. The following example demonstrates how to produce a 3-color PNG of the above model using the scattered light wavelengths:

```
import numpy as np
from PIL import Image

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

m = ModelOutput('simple_cube.rtout')
image = m.get_image(inclination=0, distance=300 * pc, units='MJy/sr')

# Extract the slices we want to use for red, green, and blue
r = image.val[:, :, 17]
g = image.val[:, :, 18]
```

```
b = image.val[:, :, 19]

# Now we need to rescale the values we want to the range 0 to 255, clip values
# outside the range, and convert to unsigned 8-bit integers. We also use a sqrt
# stretch (hence the ** 0.5)

r = np.clip((r / 0.5) ** 0.5 * 255., 0., 255.)
r = np.array(r, dtype=np.uint8)

g = np.clip((g / 2) ** 0.5 * 255., 0., 255.)
g = np.array(g, dtype=np.uint8)

b = np.clip((b / 4.) ** 0.5 * 255., 0., 255.)
b = np.array(b, dtype=np.uint8)

# We now convert to image objects
image_r = Image.fromarray(r)
image_g = Image.fromarray(g)
image_b = Image.fromarray(b)

# And finally merge into a single 3-color image
img = Image.merge("RGB", (image_r, image_g, image_b))

# By default, the image will be flipped, so we need to fix this
img = img.transpose(Image.FLIP_TOP_BOTTOM)

img.save('simple_cube_rgb.png')
```

which gives:

Alternatively, you can write out the required images to FITS format, then use the make_rgb_image function in APLpy to make the 3-color images.

Making animations

In this tutorial, we will find out how to make animations from Hyperion output.

Example model

To start with we will use a model very similar to Plotting and writing images but this time we only compute the image in one wavelength bin, but for a number of different viewing angles:

```
import numpy as np

from hyperion.model import Model
from hyperion.util.constants import pc, lsun

# Initialize model
m = Model()
```

```
# Set up 64x64x64 cartesian grid
w = np.linspace(-pc, pc, 64)
m.set_cartesian_grid(w, w, w)

# Add density grid with constant density and add a higher density cube inside to
# cause a shadow.
density = np.ones(m.grid.shape) * 1e-21
density[26:38, 26:38, 26:38] = 1.e-18
m.add_density_grid(density, 'kmh_lite.hdf5')

# Add a point source in the center
s = m.add_point_source()
s.position = (0.4 * pc, 0., 0.)
s.luminosity = 1000 * lsun
s.temperature = 6000.

# Add multi-wavelength image for a single viewing angle
image = m.add_peeled_images(sed=False, image=True)
image.set_wavelength_range(1, 190., 210.)
image.set_viewing_angles(np.repeat(45., 36), np.linspace(5., 355., 36))
image.set_image_size(400, 400)
image.set_image_limits(-1.5 * pc, 1.5 * pc, -1.5 * pc, 1.5 * pc)

# Set runtime parameters. We turn off scattering for the imaging since it is not
# important at these wavelengths.
m.set_n_initial_iterations(5)
m.set_raytracing(True)
m.set_n_photons(initial=4e6, imaging=0,
                raytracing_sources=1, raytracing_dust=1e7)

# Write out input file
m.write('flyaround_cube.rtin')
m.run('flyaround_cube.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

Making a fly-around movie

The following script describes how to generate PNG frames for an animation:

```
import os

import numpy as np
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Create output directory if it does not already exist
if not os.path.exists('frames'):
    os.mkdir('frames')

# Open model
m = ModelOutput('flyaround_cube.rtout')
```

```
# Read image from model
image = m.get_image(distance=300 * pc, units='MJy/sr')

# image.val is now an array with four dimensions (n_view, n_y, n_x, n_wav)

for iview in range(image.val.shape[0]):

    # Open figure and create axes
    fig = plt.figure(figsize=(3, 3))
    ax = fig.add_subplot(1, 1, 1)

    # This is the command to show the image. The parameters vmin and vmax are
    # the min and max levels for the grayscale (remove for default values).
    # The colormap is set here to be a heat map. Other possible heat maps
    # include plt.cm.gray (grayscale), plt.cm.gist_yarg (inverted grayscale),
    # plt.cm.jet (default, colorful). The np.sqrt() is used to plot the
    # images on a sqrt stretch.
    ax.imshow(np.sqrt(image.val[iview, :, :, 0]), vmin=0, vmax=np.sqrt(2000.),
              cmap=plt.cm.gist_heat, origin='lower')

    # Save figure. The facecolor='black' and edgecolor='black' are for
    # esthetics, and hide the axes
    fig.savefig('frames/frame_%05i.png' % iview,
                facecolor='black', edgecolor='black')

    # Close figure
    plt.close(fig)
```

The frames can then be combined into a GIF animation using ImageMagick:

```
$ convert -delay 10 -adjoin frames/*.png movie.gif
```

The delay value is the delay between frames in 1/100ths of a second. The result is the following:

Visualizing physical quantities for regular 3-d grids

As described in Extracting physical quantities, it is easy to extract quantities such as density, specific_energy, and temperature from the output model files. In this tutorial, we see how to visualize this information efficiently.

Cartesian grid example

We first set up a model of a box containing 100 sources heating up dust:

```
import random
random.seed('hyperion')  # ensure that random numbers are the same every time

import numpy as np
from hyperion.model import Model
from hyperion.util.constants import pc, lsun

# Define cell walls
x = np.linspace(-10., 10., 101) * pc
y = np.linspace(-10., 10., 101) * pc
z = np.linspace(-10., 10., 101) * pc
```

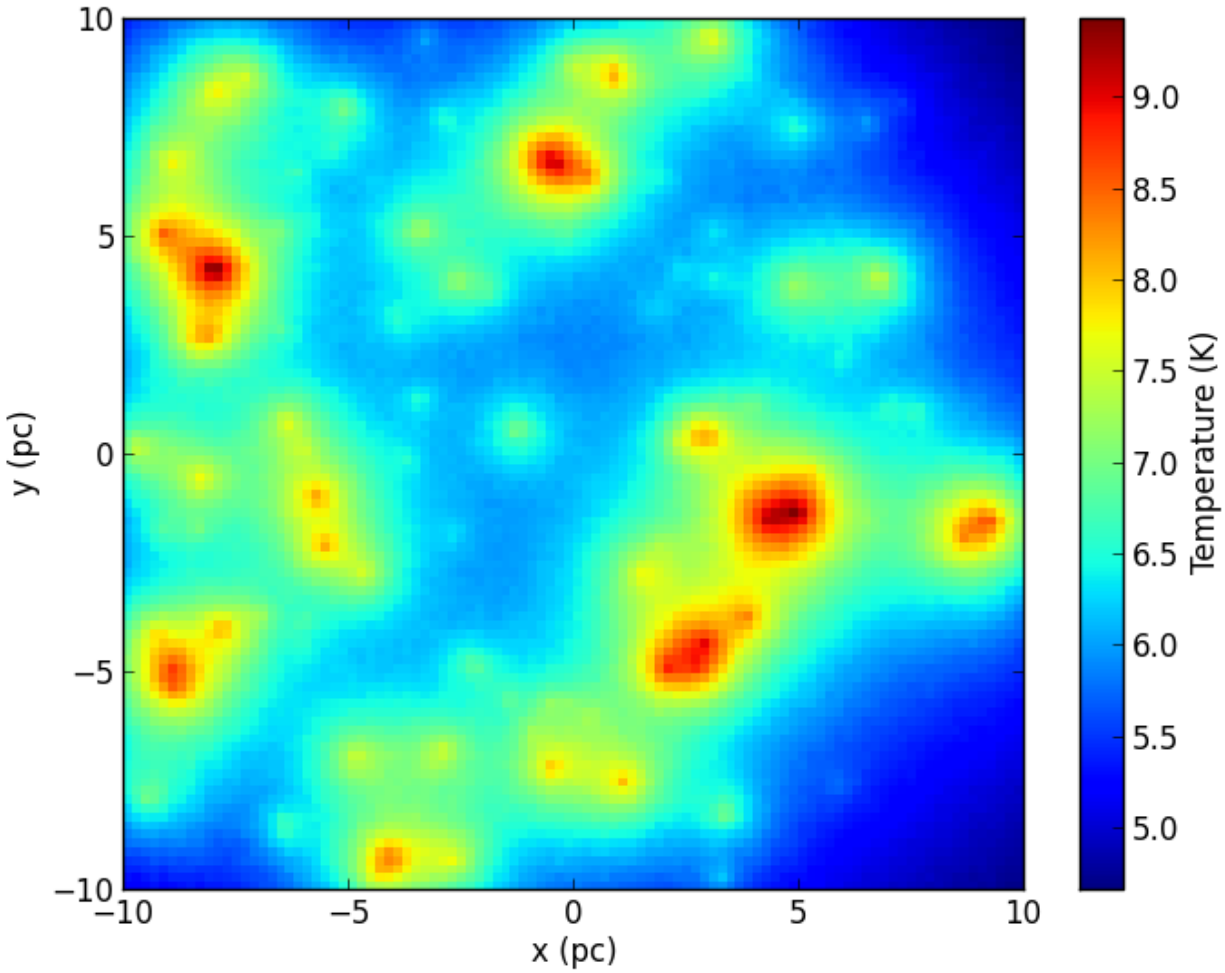
```
# Initialize model and set up density grid
m = Model()
m.set_cartesian_grid(x, y, z)
m.add_density_grid(np.ones((100, 100, 100)) * 1.e-20, 'kmh_lite.hdf5')

# Generate random sources
for i in range(100):
    s = m.add_point_source()
    xs = random.uniform(-10., 10.) * pc
    ys = random.uniform(-10., 10.) * pc
    zs = random.uniform(-10., 10.) * pc
    s.position = (xs, ys, zs)
    s.luminosity = 10. ** random.uniform(0., 3.) * lsun
    s.temperature = random.uniform(3000., 8000.)

# Specify that the specific energy and density are needed
m.conf.output.output_specific_energy = 'last'
m.conf.output.output_density = 'last'

# Set the number of photons
m.set_n_photons(initial=10000000, imaging=0)

# Write output and run model
m.write('quantity_cartesian.rtin')
m.run('quantity_cartesian.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

We can then use the `get_quantities` method described above to produce a density-weighted temperature map collapsed in the z direction:

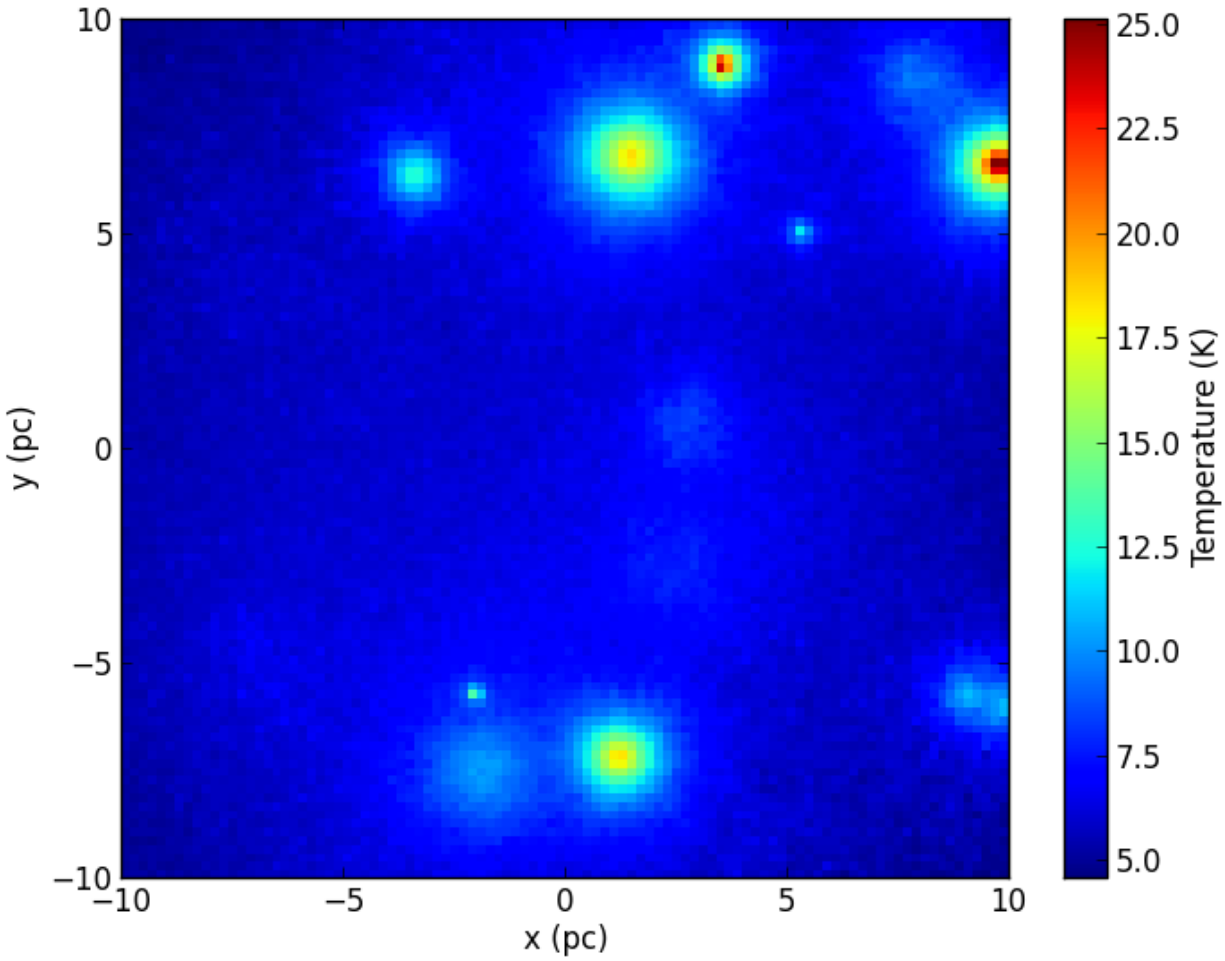
```
import numpy as np
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

# Read in the model
m = ModelOutput('quantity_cartesian.rtout')

# Extract the quantities
g = m.get_quantities()

# Get the wall positions in pc
xw, yw = g.x_wall / pc, g.y_wall / pc

# Make a 2-d grid of the wall positions (used by pcoloarmesh)
X, Y = np.meshgrid(xw, yw)

# Calculate the density-weighted temperature
weighted_temperature = (np.sum(g['temperature'][0].array
                               * g['density'][0].array, axis=2)
                        / np.sum(g['density'][0].array, axis=2))

# Make the plot
fig = plt.figure()
```

```
ax = fig.add_subplot(1, 1, 1)
c = ax.pcolormesh(X, Y, weighted_temperature)
ax.set_xlim(xw[0], xw[-1])
ax.set_xlim(yw[0], yw[-1])
ax.set_xlabel('x (pc)')
ax.set_ylabel('y (pc)')
cb = fig.colorbar(c)
cb.set_label('Temperature (K)')
fig.savefig('weighted_temperature_cartesian.png', bbox_inches='tight')
```



Of course, we can also plot individual slices:

```
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)
c = ax.pcolormesh(X, Y, g['temperature'][0].array[:, 49, :])
ax.set_xlim(xw[0], xw[-1])
ax.set_xlim(yw[0], yw[-1])
ax.set_xlabel('x (pc)')
ax.set_ylabel('y (pc)')
cb = fig.colorbar(c)
cb.set_label('Temperature (K)')
fig.savefig('sliced_temperature_cartesian.png', bbox_inches='tight')
```



Spherical polar grid example

Polar grids are another interest case, because one might want to plot the result in polar or cartesian coordinates. To demonstrate this, we set up a simple example with a star surrounded by a flared disk:

```
from hyperion.model import AnalyticalYSOModel
from hyperion.util.constants import lsun, rsun, tsun, msun, au

# Initialize model and set up density grid
m = AnalyticalYSOModel()

# Set up the central source
m.star.radius = rsun
m.star.temperature = tsun
m.star.luminosity = lsun

# Set up a simple flared disk
d = m.add_flared_disk()
d.mass = 0.001 * msun
d.rmin = 0.1 * au
d.rmax = 100. * au
d.p = -1
d.beta = 1.25
```

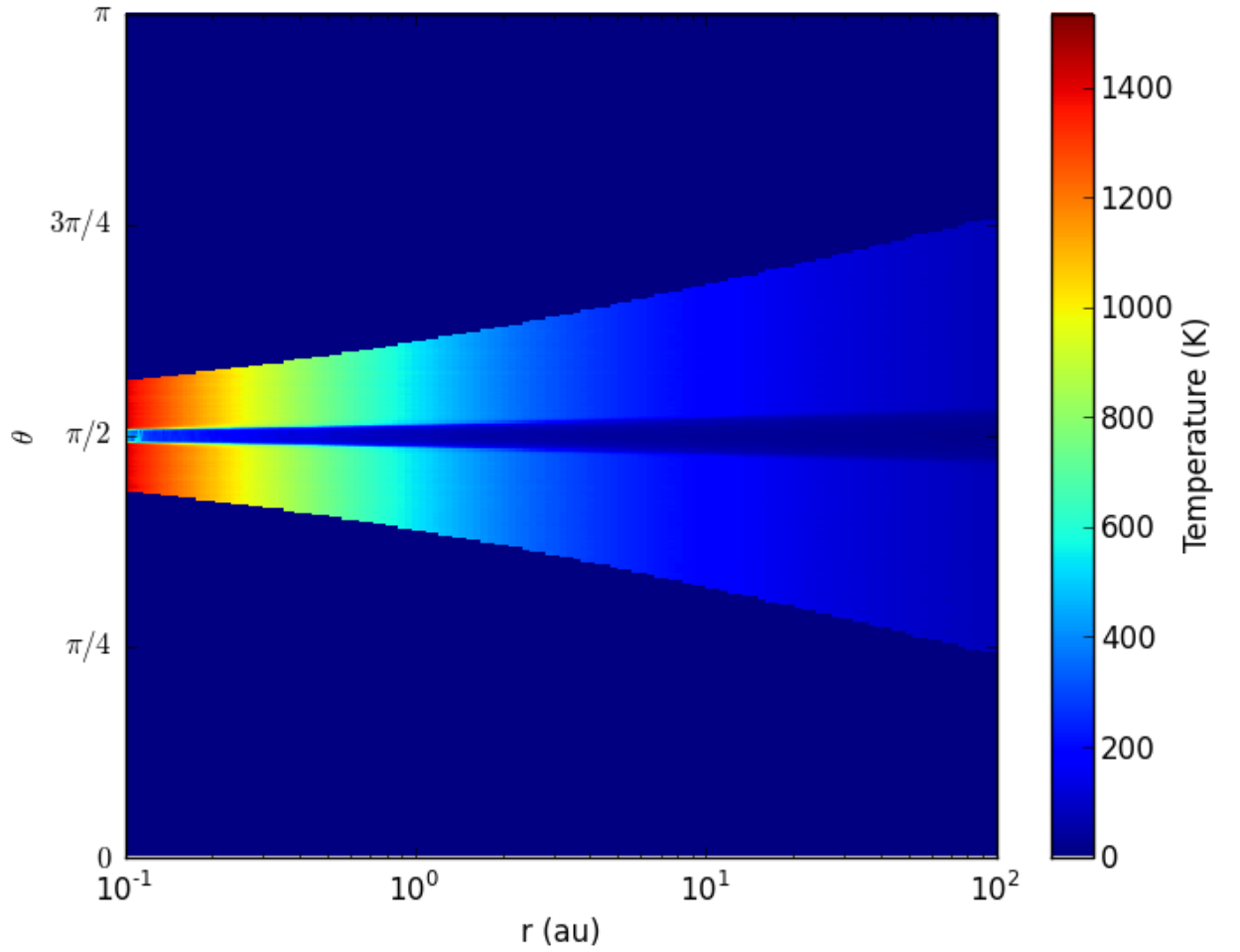
```
d.h_0 = 0.01 * au
d.r_0 = au
d.dust = 'kmh_lite.hdf5'

# Specify that the specific energy and density are needed
m.conf.output.output_specific_energy = 'last'
m.conf.output.output_density = 'last'

# Set the number of photons
m.set_n_photons(initial=1000000, imaging=0)

# Set up the grid
m.set_spherical_polar_grid_auto(400, 300, 1)

# Use MRW and PDA
m.set_mrw(True)
m.set_pda(True)

# Write output and run model
m.write('quantity_spherical.rtin')
m.run('quantity_spherical.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

Making a plot of temperature in (r, theta) space is similar to before:

```
import numpy as np
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import au

# Read in the model
m = ModelOutput('quantity_spherical.rtout')

# Extract the quantities
g = m.get_quantities()

# Get the wall positions for r and theta
rw, tw = g.r_wall / au, g.t_wall

# Make a 2-d grid of the wall positions (used by pcolormesh)
R, T = np.meshgrid(rw, tw)

# Make a plot in (r, theta) space
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1)
c = ax.pcolormesh(R, T, g['temperature'][0].array[0, :, :])
ax.set_xscale('log')
ax.set_xlim(rw[1], rw[-1])
ax.set_ylim(tw[0], tw[-1])
ax.set_xlabel('r (au)')
ax.set_ylabel(r'$\theta$')
ax.set_yticks([np.pi, np.pi * 0.75, np.pi * 0.5, np.pi * 0.25, 0.])
ax.set_yticklabels([r'$\pi$', r'$3\pi/4$', r'$\pi/2$', r'$\pi/4$', r'$0$'])
cb = fig.colorbar(c)
```

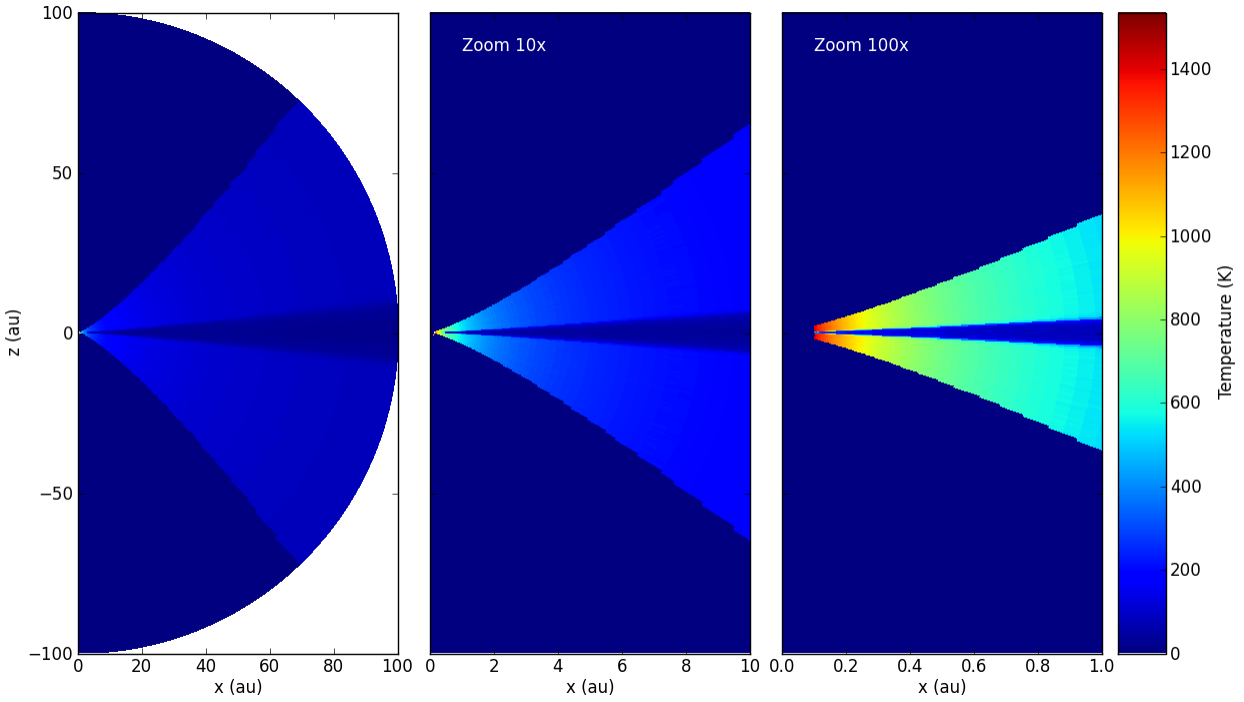
```
cb.set_label('Temperature (K)')
fig.savefig('temperature_spherical_rt.png', bbox_inches='tight')
```



Making a plot in spherical coordinates instead is in fact also straightforward:

```
# Calculate the position of the cell walls in cartesian coordinates
R, T = np.meshgrid(rw, tw)
X, Z = R * np.sin(T), R * np.cos(T)

# Make a plot in (x, z) space for different zooms
fig = plt.figure(figsize=(16, 8))

ax = fig.add_axes([0.1, 0.1, 0.2, 0.8])
c = ax.pcolormesh(X, Z, g['temperature'][0].array[0, :, :])
ax.set_xlim(X.min(), X.max())
ax.set_ylim(Z.min(), Z.max())
ax.set_xlabel('x (au)')
ax.set_ylabel('z (au)')

ax = fig.add_axes([0.32, 0.1, 0.2, 0.8])
c = ax.pcolormesh(X, Z, g['temperature'][0].array[0, :, :])
ax.set_xlim(X.min() / 10., X.max() / 10.)
ax.set_ylim(Z.min() / 10., Z.max() / 10.)
ax.set_xlabel('x (au)')
ax.set_yticklabels('')
```

```
ax.text(0.1, 0.95, 'Zoom 10x', ha='left', va='center',
        transform=ax.transAxes, color='white')

ax = fig.add_axes([0.54, 0.1, 0.2, 0.8])
c = ax.pcolormesh(X, Z, g['temperature'][0].array[0, :, :])
ax.set_xlim(X.min() / 100., X.max() / 100)
ax.set_ylim(Z.min() / 100, Z.max() / 100)
ax.set_xlabel('x (au)')
ax.set_yticklabels('')
ax.text(0.1, 0.95, 'Zoom 100x', ha='left', va='center',
        transform=ax.transAxes, color='white')

ax = fig.add_axes([0.75, 0.1, 0.03, 0.8])
cb = fig.colorbar(c, cax=ax)
cb.set_label('Temperature (K)')

fig.savefig('temperature_spherical_xz.png', bbox_inches='tight')
```



Visualizing physical quantities from adaptive grids with yt

As described in Extracting physical quantities, it is easy to extract quantities such as density, specific_energy, and temperature from the output model files. In this tutorial, we see how to visualize this information efficiently for AMR and Octree grids.

Fortunately, we can just make use of the excellent yt package that has been developed for that purpose! Hyperion includes convenience methods to convert grid objects to objects that you can use in yt.

If you extract quantities from an output file with:

```
grid = m.get_quantities()
```

then `grid` will be an `AMRGrid` or `OctreeGrid` grid object. This object contains all the information about the grid geometry, as well as the physical quantities such as density, temperature, and specific energy (depending on how you

configured the model). You can then simply do:

```
pf = grid.to_yt()
```

where `pf` is a `StaticOutput` yt object! This can then be used as a normal dataset in yt. For example, we can easily make projections of density and temperature along the y-axis:

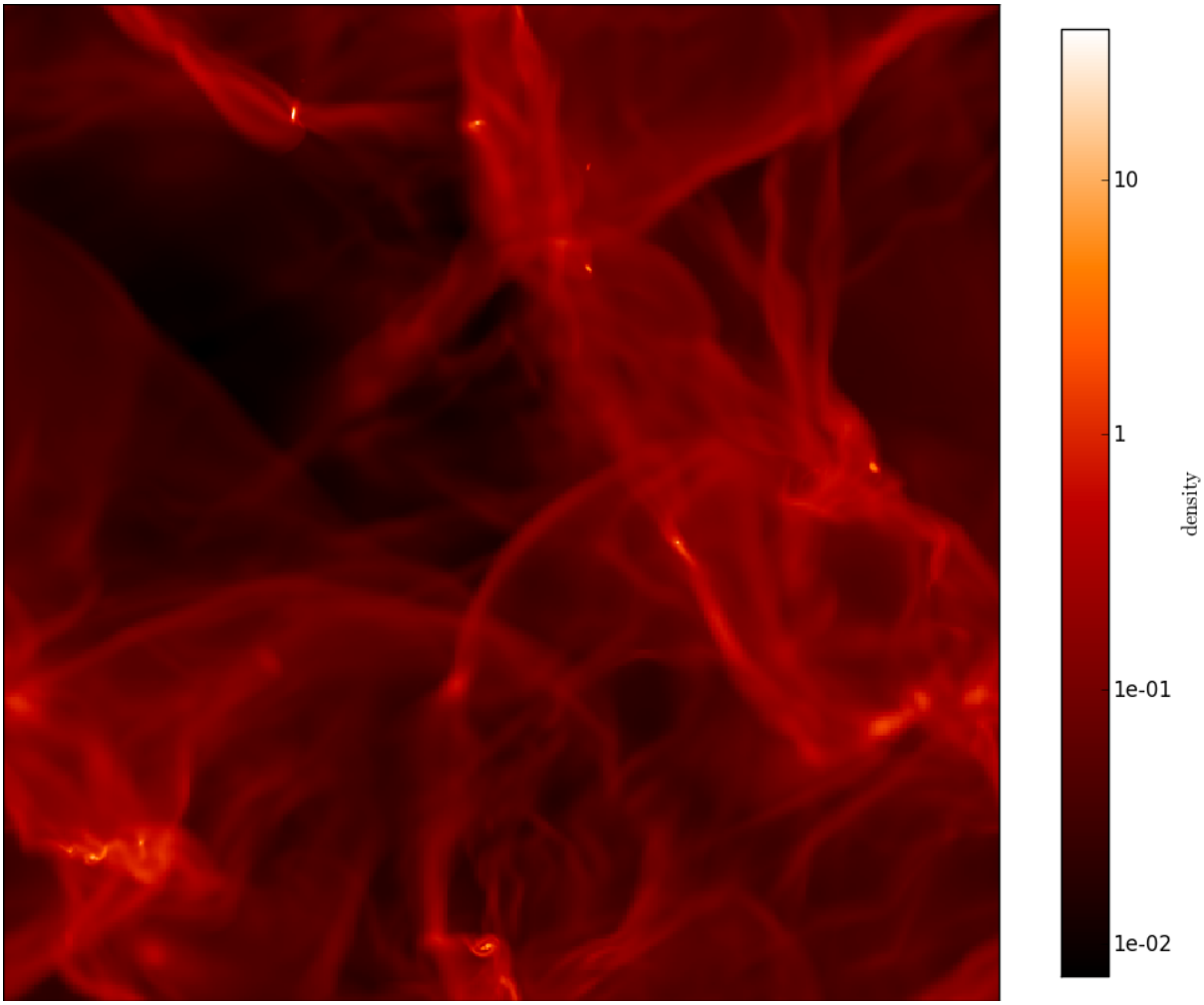
```
from yt.mods import ProjectionPlot

prj = ProjectionPlot(pf, 'y', ['density', 'temperature'],
                     center=[0.0, 0.0, 0.0])
prj.set_cmap('temperature', 'gist_heat')
prj.set_cmap('density', 'gist_heat')
prj.set_log('density', True)
prj.save()
```

The `to_yt` method is also available for regular cartesian grids, but not for the spherical or cylindrical polar grids.

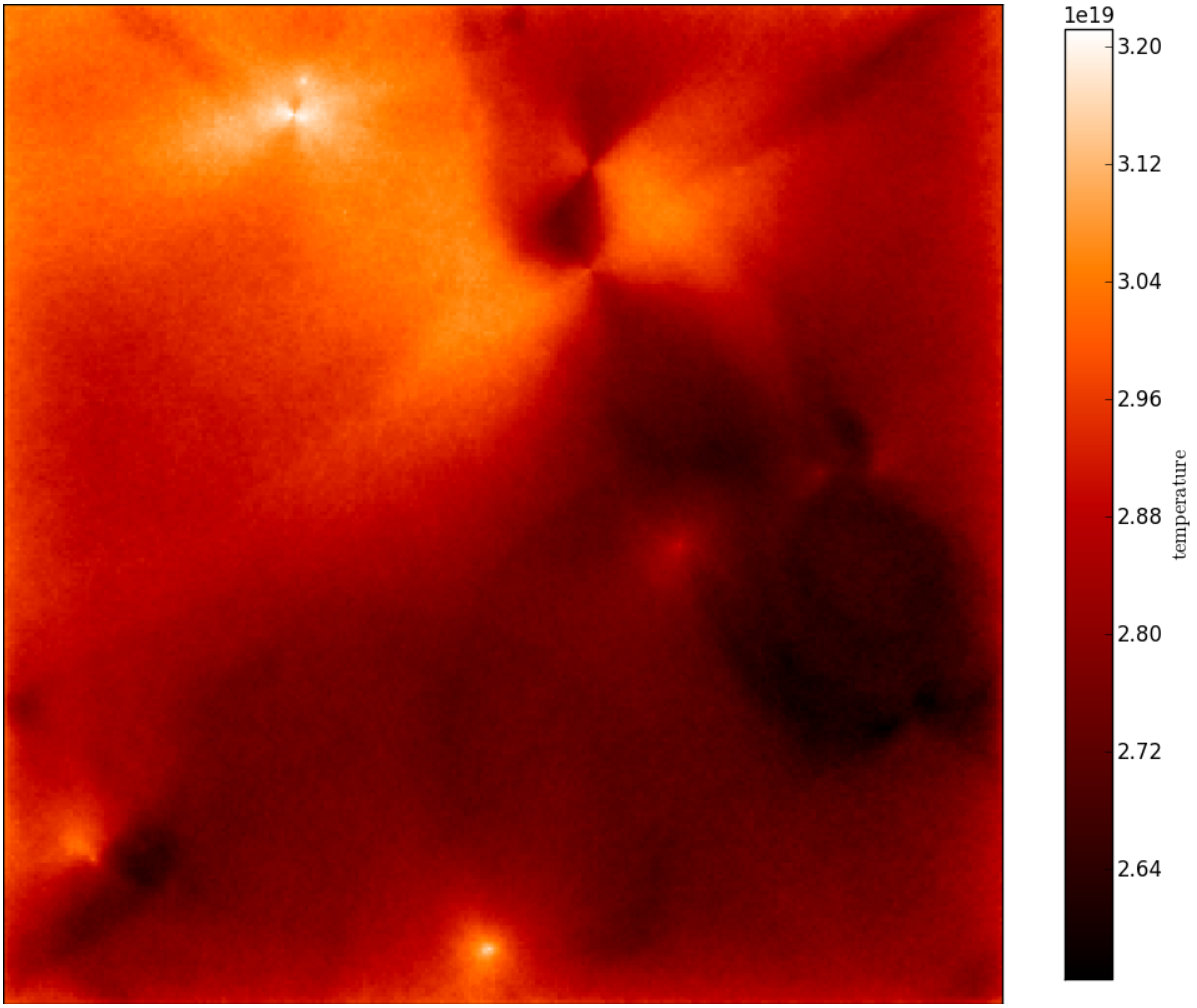
Note: At the moment, the method used to plot Octrees is very inefficient, so plotting these will be very slow.

Projection plots are just a very small fraction of the functionality of yt - you should have a careful look at their documentation to find out about all the available functionality!

If we apply this to the output for the radiative transfer model on the hydrodynamical simulation in Robitaille (2011), the density looks like:



and the temperature looks like:



3.6.3 Example models

Typical Analytical YSO Model

The following example model sets up the Class I model from Whitney et al (2003) For now, this model does not include the accretion luminosity, but this will be added in the future. First, we set up the model using the *AnalyticalYSOModel* class:

```
import numpy as np

from hyperion.model import AnalyticalYSOModel
from hyperion.util.constants import rsun, lsun, au, msun, yr, c

# Initalize the model
m = AnalyticalYSOModel()

# Read in stellar spectrum
wav, fnu = np.loadtxt('kt04000g+3.5z-2.0.ascii', unpack=True)
nu = c / (wav * 1.e-4)

# Set the stellar parameters
m.star.radius = 2.09 * rsun
```

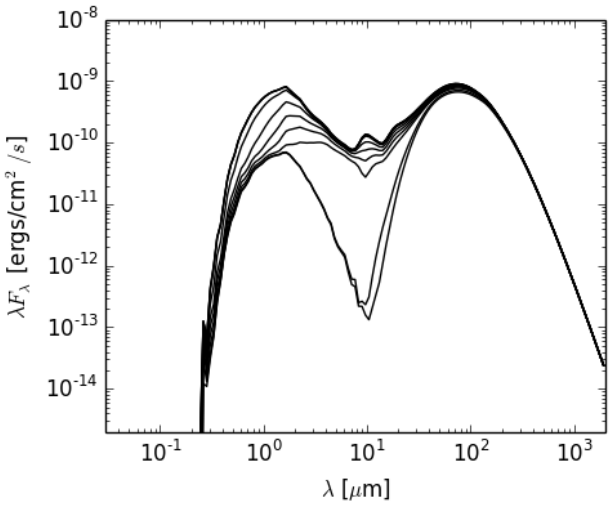
```
m.star.spectrum = (nu, fnu)
m.star.luminosity = lsun
m.star.mass = 0.5 * msun

# Add a flared disk
disk = m.add_flared_disk()
disk.mass = 0.01 * msun
disk.rmin = 7 * m.star.radius
disk.rmax = 200 * au
disk.r_0 = m.star.radius
disk.h_0 = 0.01 * disk.r_0
disk.p = -1.0
disk.beta = 1.25
disk.dust = 'kmh_lite.hdf5'

# Add an Ulrich envelope
envelope = m.add_ulrich_envelope()
envelope.rc = disk.rmax
envelope.mdot = 5.e-6 * msun / yr
envelope.rmin = 7 * m.star.radius
envelope.rmax = 5000 * au
envelope.dust = 'kmh_lite.hdf5'

# Add a bipolar cavity
cavity = envelope.add_bipolar_cavity()
cavity.power = 1.5
cavity.theta_0 = 20
cavity.r_0 = envelope.rmax
cavity.rho_0 = 5e4 * 3.32e-24
cavity.rho_exp = 0.
cavity.dust = 'kmh_lite.hdf5'

# Use raytracing to improve s/n of thermal/source emission
m.set_raytracing(True)

# Use the modified random walk
m.set_mrw(True, gamma=2.)

# Set up grid
m.set_spherical_polar_grid_auto(399, 199, 1)

# Set up SED
sed = m.add_peeled_images(sed=True, image=False)
sed.set_viewing_angles(np.linspace(0., 90., 10), np.repeat(45., 10))
sed.set_wavelength_range(150, 0.02, 2000.)

# Set number of photons
m.set_n_photons(initial=1e6, imaging=1e6,
                raytracing_sources=1e4, raytracing_dust=1e6)

# Set number of temperature iterations and convergence criterion
m.set_n_initial_iterations(10)
m.set_convergence(True, percentile=99.0, absolute=2.0, relative=1.1)

# Write out file
m.write('class1_example.rtin')
m.run('class1_example.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!). You will also need the stellar photosphere model from `here`.

The model takes a few minutes to run on 12 processes (a little less than an hour in serial mode). We can then proceed for example to plotting the SED:

```
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.constants import pc

mo = ModelOutput('class1_example.rtout')
sed = mo.get_sed(aperture=-1, distance=140. * pc)

fig = plt.figure(figsize=(5, 4))
ax = fig.add_subplot(1, 1, 1)
ax.loglog(sed.wav, sed.val.transpose(), color='black')
ax.set_xlim(0.03, 2000.)
ax.set_ylim(2.e-15, 1e-8)
ax.set_xlabel(r'$\lambda$ [$\mu$m]')
ax.set_ylabel(r'$\lambda F_\lambda$ [ergs/cm$^2/s$]')
fig.savefig('class1_example_sed.png', bbox_inches='tight')
```

which gives:



which is almost identical to the bottom left panel of Figure 3a of Whitney et al (2003) (the differences being due to slightly different dust properties).

3.6.4 Advanced

How to efficiently compute pure scattering models

In some cases, for example if the wavelength is short enough, it is possible to ignore dust emission when computing images. In such cases, we can make Hyperion run faster by disabling the temperature calculation as described in *Scattered-light images*, and also by producing images only at select wavelengths using *Monochromatic radiative transfer*. The following model demonstrates how to make an image of the central region of a flared disk in order to image the inner rim:

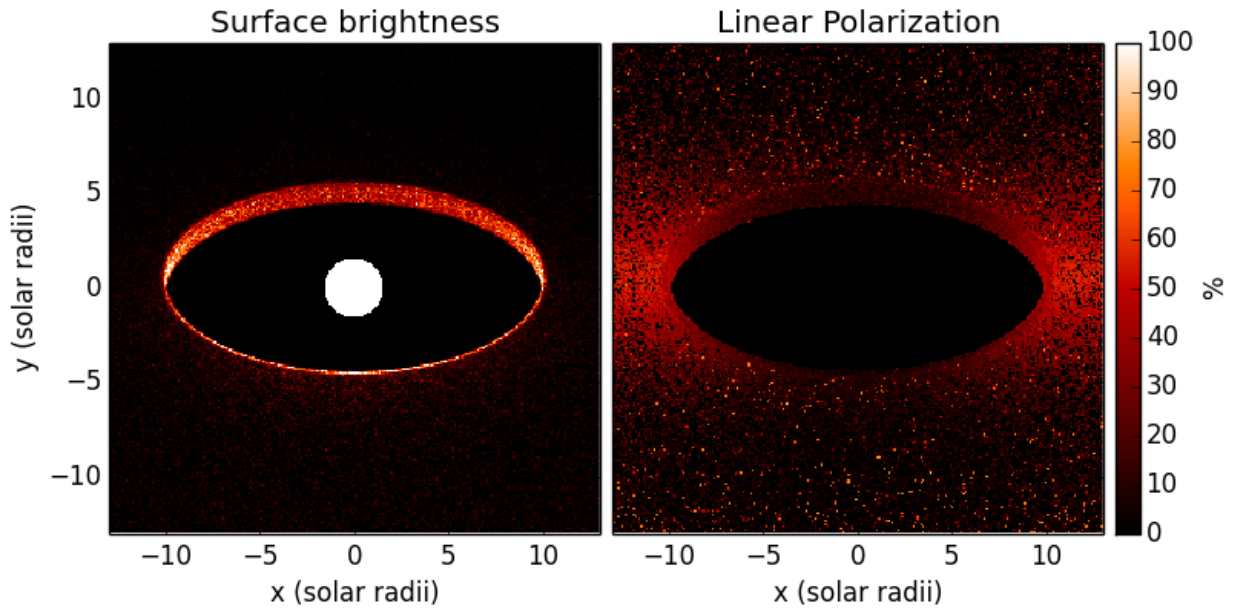
```
from hyperion.model import AnalyticalYSOModel
from hyperion.util.constants import au, lsun, rsun, tsun, msun

# Initialize model
m = AnalyticalYSOModel()

# Set up star
m.star.radius = 1.5 * rsun
m.star.temperature = tsun
m.star.luminosity = lsun

# Set up disk
d = m.add_flared_disk()
d.rmin = 10 * rsun
d.rmax = 30. * au
d.mass = 0.01 * msun
d.p = -1
d.beta = 1.25
d.r_0 = 10. * au
d.h_0 = 0.4 * au
d.dust = 'kmh_lite.hdf5'

# Set up grid
m.set_spherical_polar_grid_auto(400, 100, 1)

# Don't compute temperatures
m.set_n_initial_iterations(0)

# Don't re-emit photons
m.set_kill_on_absorb(True)

# Use raytracing (only important for source here, since no dust emission)
m.set_raytracing(True)

# Compute images using monochromatic radiative transfer
m.set_monochromatic(True, wavelengths=[1.])

# Set up image
i = m.add_peeled_images()
i.set_image_limits(-13 * rsun, 13 * rsun, -13. * rsun, 13 * rsun)
i.set_image_size(256, 256)
i.set_viewing_angles([60.], [20.])
i.set_wavelength_index_range(1, 1)
i.set_stokes(True)

# Set number of photons
m.set_n_photons(imaging_sources=10000000, imaging_dust=0,
                raytracing_sources=100000, raytracing_dust=0)

# Write out the model and run it in parallel
m.write('pure_scattering.rtin')
m.run('pure_scattering.rtout', mpi=True)
```

Note: If you want to run this model you will need to download the `kmh_lite.hdf5` dust file into the same directory as the script above (**disclaimer**: do not use this dust file outside of these tutorials!).

Once this model has run, we can make a plot of the image (including a linear polarization map):

```
import matplotlib.pyplot as plt
from hyperion.model import ModelOutput
from hyperion.util.constants import pc

mo = ModelOutput('pure_scattering.rtout')

image_fnu = mo.get_image(inclination=0, units='MJy/sr', distance=300. * pc)
image_pol = mo.get_image(inclination=0, stokes='linpol')

fig = plt.figure(figsize=(8, 8))

# Make total intensity sub-plot

ax = fig.add_axes([0.1, 0.3, 0.4, 0.4])
ax.imshow(image_fnu.val[:, :, 0], extent=[-13, 13, -13, 13],
          interpolation='none', cmap=plt.cm.gist_heat,
          origin='lower', vmin=0., vmax=4e9)
ax.set_xlim(-13., 13.)
ax.set_ylim(-13., 13.)
ax.set_xlabel("x (solar radii)")
ax.set_ylabel("y (solar radii)")
ax.set_title("Surface brightness")

# Make linear polarization sub-plot

ax = fig.add_axes([0.51, 0.3, 0.4, 0.4])
im = ax.imshow(image_pol.val[:, :, 0] * 100., extent=[-13, 13, -13, 13],
               interpolation='none', cmap=plt.cm.gist_heat,
               origin='lower', vmin=0., vmax=100.)
ax.set_xlim(-13., 13.)
ax.set_ylim(-13., 13.)
ax.set_xlabel("x (solar radii)")
ax.set_title("Linear Polarization")
ax.set_yticklabels('')

axcb = fig.add_axes([0.92, 0.3, 0.02, 0.4])
cb=plt.colorbar(im, cax=axcb)
cb.set_label('%')
fig.savefig('pure_scattering_inner_disk.png', bbox_inches='tight')
```

which gives:



This model takes under 4 minutes to run on 8 cores, which is less than would normally be required to produce an image with this signal-to-noise in scattered light.

How to set the luminosity for an external radiation field

Two source types, *ExternalSphericalSource* and *ExternalBoxSource* are available, and can be used to simulate an external radiation field (such as the interstellar radiation field or I). One of the tricky parameters to set is the luminosity, because one often knows what the mean intensity of the interstellar radiation field should be, but not the total luminosity emitted from a spherical or box surface.

From empirical tests, we find that if one wants a particular value of J (the mean intensity integrated over frequency), then the luminosity should be set to $A\pi J$ where A is the area of the external source. We can check this using, as an example, the ISRF model from Mathis, Mezger, and Panagia (hereafter MMP; 1983), who find

$$4\pi J = 0.0217\,\mathrm{erg\,cm^{-2}\,s^{-1}}$$

in the solar neighborhood.

We now set up a model with a spherical grid extending to 1pc in radius, with the spectrum given by MMP83:

```
import numpy as np

from hyperion.model import Model
from hyperion.util.constants import pc, c

# The following value is taken from Mathis, Mezger, and Panagia (1983)
FOUR_PI_JNU = 0.0217

# Initialize model
m = Model()

# Set up grid
m.set_spherical_polar_grid([0., 1.001 * pc],
                           [0., np.pi],
                           [0., 2. * np.pi])
```

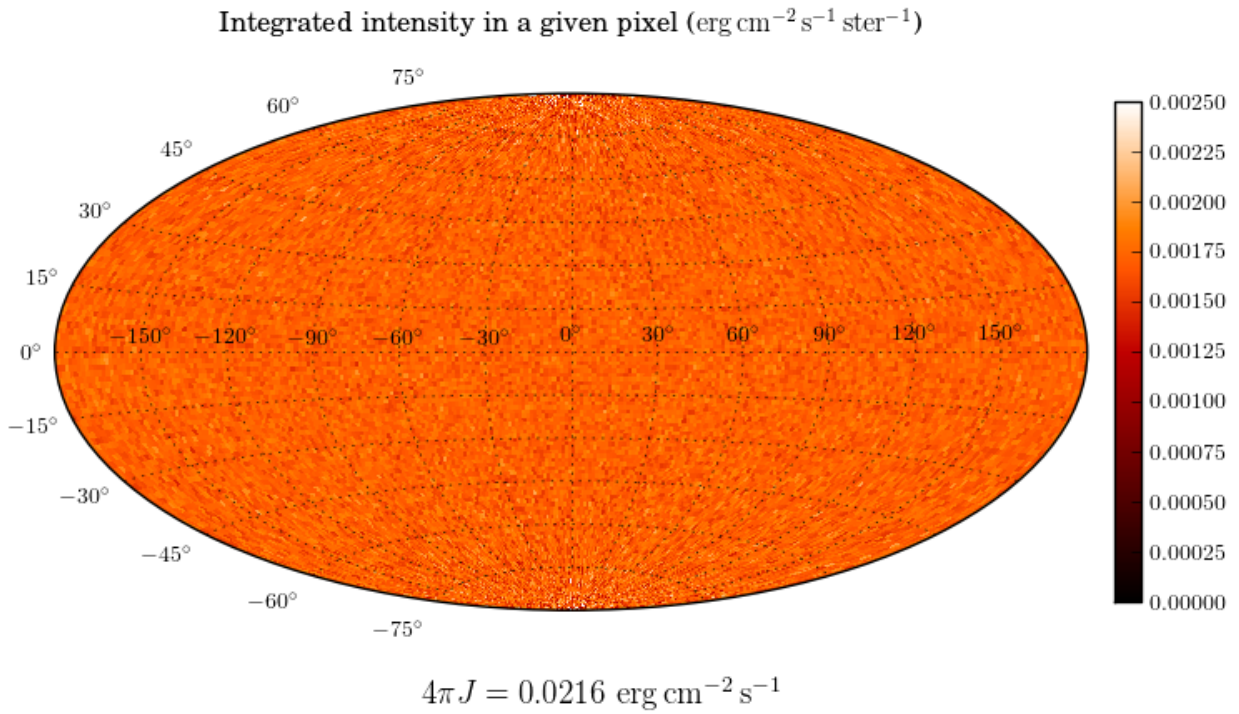
```
# Read in MMP83 spectrum
wav, jlambda = np.loadtxt('mmp83.txt', unpack=True)
nu = c / (wav * 1.e-4)
jnu = jlambda * wav / nu

# Set up the source - note that the normalization of the spectrum is not
# important - the luminosity is set separately.
s = m.add_external_spherical_source()
s.radius = pc
s.spectrum = (nu, jnu)
s.luminosity = np.pi * pc * pc * FOUR_PI_JNU

# Add an inside observer with an all-sky camera
image = m.add_peeled_images(sed=False, image=True)
image.set_inside_observer((0., 0., 0.))
image.set_image_limits(180., -180., -90., 90.)
image.set_image_size(256, 128)
image.set_wavelength_range(100, 0.01, 1000.)

# Use raytracing for high signal-to-noise
m.set_raytracing(True)

# Don't compute the temperature
m.set_n_initial_iterations(0)

# Only include photons from the source (since there is no dust)
m.set_n_photons(imaging=0,
                raytracing_sources=10000000,
                raytracing_dust=0)

# Write out and run the model
m.write('example_isrf.rtin')
m.run('example_isrf.rtout')
```

To run this model, you will need the `mmp83.txt` file which contains the spectrum of the interstellar radiation field. We have set up an observer inside the grid to make an all-sky integrated intensity map:

```
import numpy as np
import matplotlib.pyplot as plt

from hyperion.model import ModelOutput
from hyperion.util.integrate import integrate_loglog

# Use LaTeX for plots
plt.rc('text', usetex=True)

# Open the output file
m = ModelOutput('example_isrf.rtout')

# Get an all-sky flux map
image = m.get_image(units='ergs/cm^2/s/Hz', inclination=0)

# Compute the frequency-integrated flux
fint = np.zeros(image.val.shape[:-1])
for (j, i) in np.ndindex(fint.shape):
    fint[j, i] = integrate_loglog(image.nu, image.val[j, i, :])

# Find the area of each pixel
```

```
l = np.radians(np.linspace(180., -180., fint.shape[1] + 1))
b = np.radians(np.linspace(-90., 90., fint.shape[0] + 1))
dl = l[1:] - l[:-1]
db = np.sin(b[1:]) - np.sin(b[:-1])
DL, DB = np.meshgrid(dl, db)
area = np.abs(DL * DB)

# Compute the intensity
intensity = fint / area

# Intitialize plot
fig = plt.figure()
ax = fig.add_subplot(1, 1, 1, projection='aitoff')

# Show intensity
image = ax.pcolormesh(l, b, intensity, cmap=plt.cm.gist_heat, vmin=0.0, vmax=0.0025)

# Add mean intensity
four_pi_jnu = round(np.sum(intensity * area), 4)
fig.text(0.40, 0.15, r"$4\pi J = %6.4f$ "
                     r"${\rm erg\,cm^{-2}\,s^{-1}}$" % four_pi_jnu, size=14)

# Add a colorbar
cax = fig.add_axes([0.92, 0.25, 0.02, 0.5])
fig.colorbar(image, cax=cax)

# Add title and improve esthetics
ax.set_title(r"Integrated intensity in a given pixel "
             r"(${\rm erg\,cm^{-2}\,s^{-1}\,ster^{-1}}$)", size=12, y=1.1)
ax.grid()
ax.tick_params(axis='both', which='major', labelsize=10)
cax.tick_params(axis='both', which='major', labelsize=10)

# Save the plot
fig.savefig('isrf_intensity.png', bbox_inches='tight')
```

which gives:



As we can see, the value for $4\pi J$ is almost identical to the value we initially used above.

3.7 Library of dust models

While you are encouraged to prepare your own dust properties file based on the most appropriate dust model for your problem (see Preparing dust properties), we provide a library of dust models that you can select from. Since dust files tend to be large, the final files are not directly made available - instead, you should download this file, then expand it, and run the `setup.py` script as shown to produce the final dust files:

```
tar xvzf hyperion-dust-0.1.0.tar.gz
cd hyperion-dust-0.1.0
python setup.py build_dust
```

The dust files will be generated in the `dust_files` directory. If Hyperion is updated, it may be necessary to re-run this script to update the dust files to the latest format. If this is necessary, then this will be made clear in the release announcement for Hyperion.

Disclaimer

The choice of which dust model to use is entirely yours, and you should make sure that the dust model that you pick is appropriate for the scientific problem you are trying to solve. In addition, as for the radiative transfer code itself, we cannot guarantee that the dust files are bug-free - you should sign up to the mailing list to ensure that you are informed as soon as bugs are identified and fixed.

The available dust files at this time are:

3.7.1 Kim, Martin, and Hendry (1994) dust with Henyey-Greenstein scattering

These are dust properties from Kim, Martin, and Hendry (1994), also known as KMH. The dust consists of astronomical silicates, graphite, and carbon and the size distribution was determined using a maximum entropy method. This dust type is meant to be applicable to the diffuse ISM (for low column densities) in the Galaxy.

Note: The dust properties given here are given per unit mass of **gas+dust**, assuming a gas-to-dust ratio of 141.84. This means that when using Hyperion, the total gas+dust densities should be specified.

This version of the dust file is take directly from HOCHUNK, the radiative transfer code developed by B. Whitney et al. This is the dust you should use if you want to reproduce results from that code, and it approximates the scattering with a Henyey-Greenstein function. However, if you are interested in the best version of the KMH dust, with full scattering properties, you can find this under Kim, Martin, and Hendry (1994) dust with full scattering properties.

The dust file is available in the `hyperion-dust` directory as `dust_files/kmh94_3.1_hg.hdf5` (once you have run `python setup.py build_dust`).

Rv=3.1 (`dust_files/kmh94_3.1_hg.hdf5`)

The following plot gives an overview of the dust properties (as described in Preparing dust properties):

3.7.2 Kim, Martin, and Hendry (1994) dust with full scattering properties

These are dust properties from Kim, Martin, and Hendry (1994), also known as KMH. The dust consists of astronomical silicates, graphite, and carbon and the size distribution was determined using a maximum entropy method. This dust type is meant to be applicable to the diffuse ISM (for low column densities) in the Galaxy.

Note: The dust properties given here are given per unit mass of **gas+dust**, assuming a gas-to-dust ratio of 141.84. This means that when using Hyperion, the total densities should be specified.

This version of the dust file was re-computed using the code described in Computing dust properties, and includes the full numerical scattering matrix. This is different from the version used in HOCHUNK, the radiative transfer code developed by B. Whitney et al., since that dust approximated the scattering with a Henyey-Greenstein function. If you are interested in using that dust instead, see Kim, Martin, and Hendry (1994) dust with Henyey-Greenstein scattering.

The dust file is available in the `hyperion-dust` directory as `dust_files/kmh94_3.1_full.hdf5` (once you have run `python setup.py build_dust`).

Rv=3.1 (`dust_files/kmh94_3.1_full.hdf5`)

The following plot gives an overview of the dust properties (as described in Preparing dust properties):

3.7.3 Draine et al. (2003) Milky-Way dust

These dust properties are for the carbonaceous-silicate grain model developed by Bruce Draine and collaborators. The three dust models are those for the Milky Way size distribution for Rv=3.1, 4.0, and 5.5, and the abundances and grain size distribution are taken from Weingartner and Draine (2001).

Note: The dust properties given here are given per unit mass of **dust**, and do not include the gas mass. This means

that when using Hyperion, the dust densities should be specified, not the total densities.

The Rv=3.1, 4.0, and 5.5 models are those with b_c=60ppm, 40ppm, and 30ppm respectively. The renormalization of the dust-to-gas ratio mentioned in Draine (2003) is not important here, since we give the dust properties per unit dust mass.

The dust properties presented here were recomputed with the code described in Computing dust properties, and may differ slightly from those given by Bruce Draine (we had to recompute them in order to obtain the full scattering properties which were otherwise not available).

The dust files are available in the `hyperion-dust` directory as `dust_files/d03_3.1_6.0_A.hdf5`, `dust_files/d03_4.0_4.0_A.hdf5`, and `dust_files/d03_5.5_3.0_A.hdf5` (once you have run `python setup.py build_dust`), where the first number indicates the Rv, and the second indicates b_c.

Milky-Way dust, Rv=3.1, b_c=6.0 (`dust_files/d03_3.1_6.0_A.hdf5`)

The following plot gives an overview of the dust properties (as described in Preparing dust properties):

Milky-Way dust, Rv=4.0, b_c=4.0 (`dust_files/d03_4.0_4.0_A.hdf5`)

The following plot gives an overview of the dust properties (as described in Preparing dust properties):

Milky-Way dust, Rv=5.5, b_c=3.0 (`dust_files/d03_5.5_3.0_A.hdf5`)

The following plot gives an overview of the dust properties (as described in Preparing dust properties):

If you develop dust models and would like your dust models to feature as one of the available ones on this page, please let us know!

For advanced users, we provide code and documentation to compute your own dust models:

3.7.4 Computing dust properties

A standard algorithm used to compute scattering and absorption properties by spherical dust particles is that provided by Bohren and Huffman (1983) (also known as `bhmie`). As part of the Hyperion development, we have written a wrapper around the improved version of bhmie.f developed by Bruce Draine that makes it easy to compute the dust properties for mixes of dust compositions and grain sizes. The program can be found here along with instructions for installation and usage.

Note that this code is only able to compute properties for simple spherical grains with no mantles.

Disclaimer

We cannot guarantee that the wrapper (or the original `bhmie` code) are bug-free - you should sign up to the mailing list to ensure that you are informed as soon as bugs are identified and fixed.

In order to be able to easily read computed properties into Hyperion, the easiest way is to set the `format` parameter to `2`. Then, if the `prefix` and `format` are set to e.g.:

```
'my_dust' = prefix for results
2 = output format (see README)
```

You can create a Hyperion dust object with:

```
from hyperion.dust import BHDust
d = BHDust('my_dust')
```

and as described in Preparing dust properties, you can visualize and write out the dust object with:

```
d.plot('my_dust.png')
d.write('my_dust.hdf5')
```

Please let us know if you run into any issues!

CHAPTER 4

Advanced

4.1 Advanced topics

This part of the documentation discusses topics that are more advanced, and offer more control over the input, running, and output of the radiative transfer.

4.1.1 Re-using previous models

In some cases, it can be useful to re-use the geometry, physical quantities, sources, or other parameters, from a previous model. For example, one might want to separate the calculation of the temperature/specific energy from the calculation of the images. A number of methods are available for this, and are described in the sections below.

Re-using a whole model

The simplest case is that you may want to read in a previous model, modify it, and write it out/run it again. The easiest way to do this is to use the *read()* method:

```
m = Model.read('some_model.rtin')
```

Once the model has been read in, it is possible to modify any of the parameters, add more density grids, sources, and change the parameters.

It is also possible to read in a model from an output file. In this case, what is read in are the initial parameters/settings/quantities for the model. If you would like to use the final specific energy (and optionally density if available), you can call `read` with the `only_initial=` argument set to `False`:

m = Model.read('some_model.rtout', only_initial=False)

If, instead of reading in the whole model, you want to re-use only certain aspects of a previous model, see the following sections.

Geometry

It is possible to re-use the geometry (i.e. the definition of the grid, excluding quantities such as density of specific energy) from either a previous input or output file by doing:

```
m = Model()
m.use_geometry(<filename>)
```

For example, if you create a model with:

```
m1 = Model()
m1.set_cartesian_grid([-1., 1.], [-1., 1.], [-1., 1.])
m1.add_density_grid(np.array([[[1.e-10]]]), 'kmh.hdf5')
s = m1.add_point_source()
s.luminosity = lsun
s.temperature = 6000.
m1.set_n_photons(initial=1000, imaging=1000)
m1.write('model_1.rtin')
```

and run the model to produce `model_1.rtout`, then you can create a new model that makes use of the geometry to set up a model with the same grid, but different density values and source properties by doing:

```
m2 = Model()
m2.use_geometry('model_1.rtout')
m2.add_density_grid(np.array([[[2.e-10]]]), 'kmh.hdf5')
s = m2.add_point_source()
s.luminosity = 0.5 * lsun
s.temperature = 6000.
m2.set_n_photons(initial=1000, imaging=1000)
m2.write('model_2.rtin')
```

The *use_geometry()* method can take either a previous input or output file. See *use_geometry()* for more information.

Quantities

Similarly, you can also instruct Hyperion to use the same density grid by doing:

```
m.use_quantities(<filename>, quantities=<quantities to use>)
```

As for the geometry, the file can be a previous input or output file from Hyperion. If an input file, then by default the previous input density (and optionally specific energy) will be used, whereas if an output file, then by default the final specific energy and the initial density will be used. By default, this will also read in the minimum specific energy requested for the grids, and the dust properties.

For example, in the example mentioned in *Geometry* you can do:

```
m2 = Model()
m2.use_geometry('model_1.rtout')
m2.use_quantities('model_1.rtout')
s = m2.add_point_source()
s.luminosity = lsun
s.temperature = 6000.
m2.set_n_photons(initial=1000, imaging=1000)
m2.write('model_2.rtin')
```

to use the density, specific energy, and dust from `model_1.rtout`. If you want to keep the specific energy as-is and avoid computing it further, you should make sure that you disable the calculation of the specific energy:

```
m2 = Model()
m2.use_geometry('model_1.rtout')
m2.use_quantities('model_1.rtout')
s = m2.add_point_source()
s.luminosity = lsun
s.temperature = 6000.
m2.set_n_initial_iterations(0)  # disable specific energy calculation
m2.set_n_photons(imaging=1000)  # don't specify initial number of photons
m2.write('model_2.rtin')
```

Note that you can also use just the density or just the specific energy if you wish, by using the `quantities` argument, e.g.:

```
m2.use_quantities('model_1.rtout', quantities=['density'])
```

or:

```
m2.use_quantities('model_1.rtout', quantities=['specific_energy'])
```

In the case where quantities are being read from an output file, you can also explicitly request that only the *input* quantities be read in:

```
m2.use_quantities('model_1.rtout', only_initial=True)
```

You can disable using the dust from the previous model (in case you want to change it):

```
m2.use_quantities('model_1.rtout', use_dust=False)
```

and you can also disable using the minimum specific energy:

```
m2.use_quantities('model_1.rtout', use_minimum_specific_energy=False)
```

If you are computing a model where the density is changing from one iteration to the next (for example due to dust sublimation), and if you want to use the final density, you will need to make sure that you run the initial model with the option to output the density at the last iteration:

```
m1.conf.output.output_density = 'last'
```

Finally, by default the behavior of *use_quantities()* is to read in the data, so that it can be modified, but if you do not plan to modify the density, specific energy, or dust properties, you can also simply link to the previous quantities by doing:

```
m2.use_quantities(..., copy=False)
```

For more information, see *use_quantities()*.

Sources

You can import sources from a previous input or output file with:

```
m2.use_sources('model_1.rtout')
```

This will read in the sources, and you can then modify them if needed, or add new ones to the model. For more information, see *use_sources()*.

Configuration

Several methods are available to read in the image/SED configuration, runtime parameters, and output parameters from a previous model:

```
m1.use_image_config(filename)
m1.use_run_config(filename)
m1.use_output_config(filename)
```

As for the *Sources*, it is then possible to modify these parameters, and optionally add new images. For more information, see *use_image_config()*, *use_run_config()*, and *use_output_config()*.

4.1.2 Advanced configuration

In Radiative transfer settings, we saw how to set some of the basic parameters that determine how Hyperion is run, and in this section we discuss some more advanced options.

Monochromatic radiative transfer

By default, when producing images, the radiative transfer is done over all wavelengths where radiation is emitted. Every emitted photon is propagated, and may be scattered or absorbed and re-emitted (or both) and we follow the propagation until the photon escapes the grid. When the photon is binned into an image or SED (whether making images with the binning or peeling-off algorithms), the photon is binned into a wavelength grid.

This means that producing images at exact wavelengths can be very inefficient, because it may be that 99% of the photons end up at a different wavelength and do not contribute to the images. In order to get around this problem, Hyperion also implements the concept of monochromatic radiative transfer (see section 2.6.4 of the Hyperion paper). In short, the way this algorithm works is that since the temperature has already been computed by the time the images are being computed, it is possible to consider only the propagation, scattering, and absorption of photons at the specific wavelengths/frequencies of interest.

To enable monochromatic radiative transfer, before setting the number of photons, you should call the *set_monochromatic()* method. For example, to compute images at 1, 1.2, and 1.4 microns, you would need to do:

```
m.set_monochromatic(True, wavelengths=[1., 1.2, 1.4])
```

where the `wavelength` arguments takes a list of wavelengths in microns. It is also possible to specify the frequencies in Hz:

```
m.set_monochromatic(True, frequencies=[1.e11, 2.e11])
```

When using the monochromatic mode, it is then necessary to set the number of photons separately for the photons emitted from sources and the photons emitted from dust:

```
m.set_n_photons(..., imaging_sources=1000, imaging_dust=1000, ...)
```

This should be used instead of the `imaging` option. The number of photons is the number **per wavelength/frequency**.

Scattered-light images

In some cases, one might want to compute scattered light images at wavelengths where there is no dust emission. In this case, there is no need to compute the specific energy of the dust, and there is also no need in re-emitting photons when computing images/SEDs. Therefore, one can set:

```
m.set_n_initial_iterations(0)
m.set_kill_on_absorb(True)
m.set_raytracing(True)
```

which turns off the specific energy calculation, kills photons as soon as they are first absorbed, and enables raytracing for the source emission. For the photon numbers, one can set `raytracing_dust=0` to zero, since this is not needed (there is no dust emission).

Note: This cannot be used for *all* scattered light images. For example, in a protostar, a K-band image may have a non-negligeable amount of scattered light flux originating from the inner rim of the disk. This technique can only be used when there is no dust emission.

This can be combined with the *Monochromatic radiative transfer* option described above to avoid wasting photons at wavelengths where they are not needed. When treating only scattering, you will then want to set the following options:

```
m.set_n_photons(imaging_sources=1000, imaging_dust=0,
                raytracing_sources=1000, raytracing_dust=0)
```

where the values should be adjusted to your model, but the important point is that `initial` is not needed, and `imaging_dust` and `raytracing_dust` can be set to 0.

For a full example of a model computing scattered light images, see How to efficiently compute pure scattering models.

Miscellaneous Settings

Set the maximum number of photon interactions:

```
m.set_max_interactions(100000)
```

Set the number of output bytes per floating point value for the physical arrays (4 = 32-bit, 8 = 64-bit):

```
m.set_output_bytes(4)
```

To set the minimum temperature for dust:

```
m.set_minimum_temperature(10.)
m.set_minimum_temperature([10., 5., 20.])
```

If a scalar value is specified, the same value is used for all dust types. If a list is specified, the list should have as many items as dust types, and each item corresponds to the minimum temperature for each dust type.

Similarly, to set the minimum specific energy:

```
m.set_minimum_specific_energy(1.e-4)
m.set_minimum_specific_energy([1.e-4, 1.e-5, 2.e-5])
```

By default, photon positions and cells are double-checked every 1 in 1000 cell crossings. This can be changed with *`set_propagation_check_frequency()`*:

```
m.set_propagation_check_frequency(0.01)
```

Note that values higher than 0.001 (the default) will cause the code to slow down.

4.1.3 Reducing file sizes

By default, and to be safe, links between HDF5 files are not used, since they would potentially break if the files being referred to were moved or deleted. However, this means that in a few cases, data is duplicated. There are two places where this occurs, described below.

Linking when calling Model.write

When writing out a model, the dust properties (and optionally the specific energy from a previous run) are copied into the input HDF5 file. To use links instead, you can use:

```
m = Model(...)
...
m.write(..., copy=False)
```

An additional argument, `absolute_paths`, can be used to specify whether to use links that are relative (to the input file) or absolute. The default is to use relative links, but you can use absolute links with:

```
m = Model(...)
...
m.write(..., copy=False, absolute_paths=True)
```

Linking to input files in output files

Once the Fortran code has computed an output HDF5 file, it will copy the contents of the input file into an `Input/` group in the output file, as certain information such as grid geometry can be useful in post-processing. To link to the input file instead, you can use the following method when setting up the model in your Python script:

```
m = Model(...)
...
m.set_copy_input(False)
```

In the above example, the Fortran code will now link to the input instead of copying it. In this case, the path used is the same as the path to the input file specifying when calling the Hyperion Fortran code.

4.1.4 Octree Grids

Setting up an octree grid programmatically

Octrees are hierarchical in nature, and therefore it is easiest to think about setting them up in a recursive manner. To set up an octree, we want to populate a list of booleans (referred to as `refined`).

The first value indicates whether the parent cell is sub-divided. If it is, then the the second element indicates whether the first cell of the parent cell is sub-divided. If it isn't, then the next value indicates whether the second cell of the parent cell is sub-divided. If it is, then we need to specify the booleans for all the children of that cell before we move to the third cell of the parent cell.

For example, the simplest grid is a single cell that is not sub-divided:

```
refined = [False]
```

The next simplest grid is a single grid cell that is only sub-divided once:

```
refined = [True, False, False, False, False, False, False, False, False]
```

It is easier to picture this as a hierarchy:

```
refined = [True,
              False,
              False,
              False,
              False,
              False,
              False,
              False,
              False,
              ]
```

If we sub-divide the third sub-cell in the parent cell into cells that are themselves not sub-divided, we get:

```
refined = [True,
             False,
             False,
             True,
               False,
               False,
               False,
               False,
               False,
               False,
               False,
               False,
             False,
             False,
             False,
             False,
             False,
             ]
```

and so on. The order of the sub-cells is first along x, then along y, then along z.

In practice, we can make use of a recursive function to set up such a grid. The following example demonstrates this:

```
# Set the random seed to make this example predictable
import random
random.seed('octree-demo')

def construct_octree(refined=[True]):

    # Loop over subcells
    for subcell in range(8):

        # Insert criterion for whether cell should be sub-divided. Here we
        # just use a random number to demonstrate.
        divide = random.random() < 0.12

        # Append boolean to overall list
        refined.append(divide)

        # If the cell is sub-divided, recursively divide it further
        if divide:
            construct_octree(refined)

    return refined

oct = construct_octree()
```

which gives a refined grid with 65 cells and sub-cells. The length of the list should always be one plus a multiple of 8.

Constructing an Octree from a set of SPH particles

Note: This functionality is currently experimental, so use with care!

Hyperion includes a function, `construct_octree`, which makes it easy to produce an Octree for a set of SPH particles, including computing the densities inside each cell. The function is used as follows:

```
from hyperion.importers.sph import construct_octree
octree = construct_octree(x, y, z, dx, dy, dz, px, py, pz, sigma, mass)
```

The arguments are:

- the center of the octree grid (`x`, `y`, `z`, which should be floating-point values)
- the half-width of the octree grid (`dx`, `dy`, `dz`, which should be floating-point values)
- the positions of the particles (`px`, `py`, `pz`, which should be 1-d Numpy arrays)
- the sigmas of the Gaussian kernel (`sigma`, which should be a 1-d Numpy array)
- the masses of the particles (`mass`, which should be a 1-d Numpy array)

Note that only Gaussian kernels are supported at this time. All values should be given in cgs. The function returns an *`OctreeGrid`* object. This can then be used to set the geometry and the density grid:

```
m.set_grid(octree)
m.add_density_grid(octree['density'][0], dust_file)
```

A criterion can be specified to halt the refinement of cells. By default, cells are no longer refined if they contain two or fewer particles. This can be changed by passing a custom function to `construct_octree` using the `stopping_criterion` argument. The function passed should take ten arguments, which are `x`, `y`, `z`, `dx`, `dy`, `dz` for the current cell, and the positions and sigmas `px`, `py`, `pz`, and `sigma` for the particles in the cell. The function should return `False` if the cell should be refined further, and `True` otherwise. For example, the default function can be written as:

```
def DEFAULT_STOPPING_CRITERION(x, y, z, dx, dy, dz, px, py, pz, sigma):
    return len(px) <= 2
```

In addition, the `construct_octree` function can take a `n_levels` argument to indicate the maximum number of levels of refinement to allow.

Writing and Reading Octree grids to disk

Computing an Octree can be a computationally expensive operation, so once it has been computed, you can write it out to disk using:

```
import h5py
f = h5py.File('my_octree_grid.hdf5', 'w')
octree.write(f)
f.close()
```

You can then read it into a separate script (e.g. the script setting up the actual model) using:

```
import h5py
from hyperion.grid import OctreeGrid
f = h5py.File('my_octree_grid.hdf5', 'r')
octree = OctreeGrid()
octree.read(f)
f.close()
```

4.1.5 AMR Grids

AMR grids are specified by nested objects in the Python, with a layout described in Coordinate grids and physical quantities. These objects can be built in several ways:

Programmatically

The following example demonstrates how an AMR grid can be built programmatically from scratch:

```
from hyperion.grid import AMRGrid
amr = AMRGrid()
for ilevel in range(nlevels):
    level = amr.add_level()
    for igrid in range(ngrids):
        grid = level.add_grid()
        grid.xmin, grid.xmax = ..., ...
        grid.ymin, grid.ymax = ..., ...
        grid.zmin, grid.zmax = ..., ...
        grid.nx, grid.ny, grid.nz = ..., ..., ...
        grid.quantities['density'] = np.array(...)
```

where `nlevels` is the number of levels in the AMR grid, and `ngrids` is the number of grids each each level. The dimensions of the `np.array(...)` on the last line should be `(nz, ny, nx)`.

Requirements

The following geometrical requirements have to be respected:

- In a given level, all grids should have the same x, y, and z resolutions, i.e. the resolution in each direction can be different, but the resolution along a particular direction has to be the same for all grids in the level.
- In a given level, the edges of all grids have to line up with a common grid defined by the widths in each direction. For example, if the cell width is `1.0` in the x direction, one cannot have a grid with `xmin=0.0` and one with `xmin=0.5` since the cell walls in the x direction for these two grids do not line up on a common grid.
- The refinement ratio between two levels (the ratio of widths of cells in a direction from one level to the next) should be a whole number. The refinement ratio can be different for different directions, and can be greater than 2.
- The boundaries of grids in a given level have to line up with cell walls in the parent level.

If these conditions are not met, then the Fortran Hyperion code will raise an error.

From simulation output

Importing functions are available in `hyperion.importers` to convert simulation output to the AMR structure required. At this time, only output from the Orion code can be read in. If the output is contained in a directory `directory`, then the AMR structure can be retrieved with:

```
from hyperion.importers import parse_orion
amr, stars = parse_orion('directory')
```

The `stars` variable is a list of `Star` instances. These `Star` instances have several attributes, which include:

- `x`, `y`, and `z` - the position of the star
- `m`, `r` - the mass and radius of the star
- `mdot` - the infall rate onto the star

These can be used for example to set up sources of emission in the model:

```
# Set up the stars
for star in stars:
    source = m.add_point_source()
    source.luminosity = lsun
    source.position = (star.x, star.y, star.z)
    source.temperature = 6000.
```

The above just creates sources with equal temperatures and luminosities, but these can also be set depending on `m`, `r`, and `mdot`.

4.1.6 Filtering logging messages in Python scripts

All messages printed by the Hyperion Python routines use the built-in logging module. This means that it is possible to filter messages based on importance. Messages can have one of several levels:

- `DEBUG` (`10`): detailed information, typically of interest only when diagnosing problems.
- `INFO` (`20`): confirmation that things are working as expected
- `WARNING` (`30`): An indication that something unexpected happened, or indicative of some problem in the near future. The program is still working as expected.
- `ERROR` (`40`): due to a more serious problem, the program has not been able to perform some function (but no exception is being raised).
- `CRITICAL` (`50`): a serious error, indicating that the program itself may be unable to continue running (but no exception is being raised).

Note that the `CRITICAL` level is unlikely to be used, since critical errors should raise Exceptions in practice.

It is possible to specify a threshold for logging messages. Messages which are less severe than this threshold will be ignored. The default threshold in Hyperion is `20` (`INFO`), indicating that all the above messages will be shown except `DEBUG`. Using 40 for example would cause only `ERROR` and `CRITICAL` messages to be shown.

By directly accessing the Hyperion logger

If you want to filter different messages in different scripts, you can directly access the logger and set the level manually:

```
from hyperion.util.logger import logger
logger.setLevel(10)
```

Using the Hyperion configuration file

If you want to always filter the same messages for all projects on a given computer, you can create a `.hyperionrc` file in your home directory, containing the following entries related to logging:

```
[logging]
color:yes
level:0
```

4.1.7 Advanced settings for peeled images

Peeloff origin

First, it is possible to change the origin relative to which the peeling-off, and therefore the image extent, are defined. This is set to `(0., 0., 0.)` by default, but you can change it using:

```
image.set_peeloff_origin((x, y, z))
```

where `x`, `y`, and `z` are floating-point values giving the cartesian coordinates of the peeloff origin. This can be used for example when doing radiative transfer calculations on a simulation, in order to create images centered on different sources.

Inside observers

It is also possible to specify that the images should be calculated from the point of view of an observer that is inside the coordinate grid, rather than at infinity. For example, if you are calculating a model of the Milky-Way Galaxy, you could place yourself at the position of the Sun using:

```
from hyperion.util.constants import kpc
image.set_inside_observer((8.5 * kpc, 0., 0.))
```

Note that in this case, the peeloff origin cannot be set, and the image limits, rather than being in cm, should be given in degrees on the sky. Note also that, like sky coordinates, the x range of the image limits should be inverted. For example:

```
image.set_image_limits(65., -65., -1., 1.)
```

will produce an image going from l=65 to l=-65, and from b=-1 to b=1.

Image depth

Finally, it is possible to restrict the depth along the line of sight from which photons should be included, with the default being:

```
image.set_depth(-np.inf, np.inf)
```

The minimum and maximum depth are measured in cm. For standard images, the depth is taken relative to the plane passing through the origin of the peeling-off. For images calculated for an observer inside the grid, the default is:

```
image.set_depth(0., np.inf)
```

where the depth is measured relative and away from the observer.

Note that in this mode, the optical depth used to calculate the peeling off is the total optical depth to the observer, not just the optical depth in the slab considered. The slab is only used to determine which emission or scattering events should be included in the image.

4.1.8 Using grids from HDF5 files

In the case of large grids, it may in some cases compute once and for all an HDF5 file containing the grid geometry and quantities, and avoid reading it when setting up the rest of the model. This can be done using *`use_grid_from_file()`*, for example:

```
from hyperion.model import Model
m = Model()
...
m.use_grid_from_file('the_grid.hdf5', dust=['kmh.hdf5'])
```

The first argument should be the name of the HDF5 file, and the `dust` argument should be a list of dust files to use, one for each dust index in the grid on disk. Once this has been done, you should not set the grid geometry nor call *add_density_grid()*.

The HDF5 file should be in the format that is written by the `write` methods on grid objects. You can do for example:

```
from hyperion.grid import CartesianGrid
g = CartesianGrid(...)
# optionally add physical quantities here
```

then write it out with:

```
import h5py
f = h5py.File('the_grid.hdf5', 'w')
g.write(f)
f.close()
```

4.1.9 Sampling in Voronoi grids

In RT computations, the need to uniformly sample points in the cells of a grid often arises. A typical example is that of the evaluation of the average value of a function (e.g., a density function) within a cell.

Whereas this task is relatively simple in regular grids, the situation is more complicated in Voronoi grids. Cells in *Voronoi grids* are indeed convex polyhedra with an arbitrary number of faces, whose shapes and volumes are determined by the intial distribution of sites.

The Voronoi helper class in Hyperion contains support for producing a list of sampling points for each cell.

Simple case: averaging of function

In the simplest case, we might want to evaluate a function in all cells (for example a function to find the density), and rather than using only the position of the sites, we want to use several random samples in each cell.

The easiest way to do this is to make use of the top-level *VoronoiGrid* class and the *evaluate_function_average()* method. Suppose we have a density function defined as

```
def density_func(x,y,z):
    # Density is proportional to the inverse
    # square of the distance from the origin.
    density = 1 / (x*x + y*y + z*z)
    return density
```

We can now generate some random sites:

```
>>> import numpy as np
>>> N = 100000
>>> x = np.random.uniform(size=N)
>>> y = np.random.uniform(size=N)
>>> z = np.random.uniform(size=N)
```

and set up a voronoi grid:

```
>>> from hyperion.grid import VoronoiGrid
>>> g = VoronoiGrid(x, y, z)
```

We can then simply call the *evaluate_function_average()* method to evaluate the function at `n_samples` sites in total, with a minimum of `min_cell_samples` samples in each cell:

```
>>> dens = g.evaluate_function_average(density_func,
                                       n_samples=1000000,
                                       min_cell_samples=5)
```

Advanced: accessing the random samples directly

In this example, we now show how to manually get the random samples in each cell and show to how to do the same function evaluation as above.

As before, we first initialise a cubic domain with unitary edge, and we fill it with randomly-placed points:

```
>>> import numpy as np
>>> N = 100000
>>> x = np.random.uniform(size=N)
>>> y = np.random.uniform(size=N)
>>> z = np.random.uniform(size=N)
>>> sites_arr = np.array([x, y, z]).transpose()
```

Next, we import the `voronoi_helpers` module and we compute the Voronoi grid `g` generated by the points in `sites_arr`:

```
>>> from hyperion.grid import voronoi_helpers as vh
>>> g = vh.voronoi_grid(sites_arr, np.array([[0, 1.], [0, 1], [0, 1]]),n_samples=1000000,min_cell_sar
INFO: Computing the tessellation via voro++ [hyperion.grid.voronoi_helpers]
```

Here we have passed to `voronoi_grid` two extra parameters related to the sampling:

- `n_samples` is the (approximate) *total* number of sampling points to be produced. For each cell, the algorithm will produce a number of sampling points that is proportional to the cell volume: larger cells will be sampled with more points than smaller cells;
- `min_cell_samples` is the *minimum* number of sampling points per cell. If a cell is small enough, it could be that no sampling points are allotted to it. This parameters forces the minimum number of sampling points to be allocated to a cell, regardless of its volume. The default value for this parameter, if omitted, is 10.

When a Voronoi grid is constructed with a positive `n_samples` parameters, it will expose two properties:

- `samples` is a list of three-dimensional vectors representing all sampling points in the domain;
- `samples_idx` is a list of indices describing, in sparse format, to which cell the points in `samples` belong.

For instance, in the example above:

```
>>> g.samples
array([[ 0.57565603,  0.9219989 ,  0.15469812],
       [ 0.58406352,  0.91473664,  0.15834503],
       [ 0.57642814,  0.93045367,  0.16361907],
       ...,
       [ 0.80025712,  0.18526818,  0.61809793],
       [ 0.78721772,  0.18366617,  0.62582103],
       [ 0.79493898,  0.17735752,  0.62803905]])
>>> g.samples_idx
array([      0,      10,      20, ..., 1147105, 1147115, 1147131], dtype=int32)
```

This means that the sampling points for the first cell have indices 0 to 10 in `g.samples`, the sampling points for the second cell have indices 10 to 20 in `g.samples`, and so on.

If now we suppose to have a density function defined as

```
def density_func(x,y,z):
    # Density is proportional to the inverse
    # square of the distance from the origin.
    density = 1 / (x*x + y*y + z*z)
    return density
```

where `x`, `y` and `z` are 1-D numpy arrays of coordinates, we can then first compute the density at all sampling points like this:

```
>>> dens_all = density_func(g.samples[:,0],g.samples[:,1],g.samples[:,2])
```

We can then compute the average density per cell with:

```
>>> dens_average = np.add.reduceat(dens_all, g.samples_idx[:-1]) / np.diff(g.samples_idx)
```

That is, `dens_average` will be an array of 1E5 elements each containing the average value of `density_func()` for each cell of the grid:

```
>>> dens_average
array([ 0.8288213 ,  3.24626334,  0.74344873, ...,  2.98673651,
        0.64962755,  0.96117706])
>>> len(dens_average)
100000
```

The following features are experimental:

4.1.10 Convolution with transmission curves

Warning: This feature is currently experimental - use at your own risk!

A new experimental feature has been added to Hyperion in recent releases, which is the ability to do on-the-fly convolution with spectral transmission curves. Until this feature was released, the only way to convolve the output from Hyperion with spectral transmission curves was to output a spectral cube with high spectral resolution and do the convolution outside of Hyperion. In most cases this is sufficient, but in cases where the images are high resolution and/or for multiple viewing angles, the memory requirements increase fast.

It is now possible to instead request that the spectral transmission convolution is done inside of Hyperion. In Hyperion, we use the term *filter* to refer to spectral transmission curves, but these can also be total system spectral transmission curves. Care must be taken when using this feature because it requires a good understanding of how the input spectral transmission curves are defined in order to obtain accurate results.

When setting up images using e.g.:

```
i = m.add_peeled_images(sed=True, image=False)
```

filters can be added by using:

```
f = i.add_filter()
```

instead of doing:

```
i.set_wavelength_range(...)
```

It is important to note that the two are incompatible - a given image group can *either* use filters, *or* a fixed wavelength range. However, multiple filters can be added to a single image group. The filter properties are then set using e.g.:

```
from astropy import units as u

f = i.add_filter()
f.name = 'F2'
f.spectral_coord = [2, 2.1, 2.2, 2.3, 2.4] * u.micron
f.transmission = [0., 50, 100, 60, 0.] * u.percent
f.detector_type = 'energy'
f.alpha = 1.
f.central_spectral_coord = 2.15 * u.micron
```

The attributes to set are the following:

- the `name` should simple be a string that can be used later to refer to the output in that particular filter.
- the `spectral_coord` attribute should be set to the x-axis of the spectral transmission curve, and can be in frequency, wavelength, or energy.
- the `transmission` attribute should be given as an array or a list of values. The absolute values do not matter, because they are re-normalized before being used in Hyperion, but the values should give the relative transmission as a function of frequency. This should not already be multiplied or divided by the frequency. It should simply give at a given frequency or wavelength, the relative probability that an energy packet will pass through the filter/system.
- the `detector_type` attribute should be set to either `'energy'` or `'photons'`. This is important because for a given input spectral shape for the emission, if a detector simply measures photons, then proportionally more photons will be detected at longer wavelengths relative to shorter wavelengths compared to the ratio of the energy detected at longer wavelengths to shorter wavelengths. When using the measurement made with the detector, it is therefore important to know whether to take into account this bias.
- the `alpha` attribute is also related to a subtle issue, which is that when measuring a flux through a given filter, what is measured is a total amount of energy or photons, but in order to convert this to a monochromatic flux F_ν, assumptions need to be made about the underlying spectral shape. Examples of this are given in the appendix of Robitaille et al. (2007). The parameter `alpha` is used to indicate that the underlying spectral shape is $\nu^\alpha F_\nu \propto \text{const}$.
- the `central_spectral_coord` attribute gives the spectral coordinate at which the monochromatic flux should be given.

Once the filters have been set up, Hyperion runs as usual. The output SEDs and images will be defined at the central wavelengths of the filters.

Note that filter convolution cannot be used in conjunction with raytracing, nor with monochromatic radiative transfer.

Finally, the two following topics are reserved for coding ninjas! They explain the HDF5 file format used for the dust files and the model files so that you can write your own library, and bypass the Python library altogether.

4.1.11 Dust HDF5 Format

Overview

Hyperion requires information on the dust properties, such as the albedo, opacity, mean opacities, and emissivities. These need to be packaged in an HDF5 format that is described below. In most cases you do not need to create these files from scratch, and you can instead use the Hyperion Python library to produce these (see Preparing dust properties). If however you want to write the files directly without the Python library, this section is for you!

Dust file HDF5 format specification

An HDF5 dust file should contain 5 datasets. The root of the file should contain the following attributes:

- `emissvar`: whether the emissivity is specified as a function of specific energy absorbed in each cell (`E`) or another quantity (but this is not supported at this time).
- `version`: this should be set to `1` - the version described in this section.
- `type`: the dust file type. At the moment, the only kind of dust file supported is one giving the four unique elements of the scattering matrix of dust as a function of scattering angle (`1`). In future, other types of dust, such as aligned grains, which require the full 16 elements, will be implemented.
- `lte`: whether the dust emissivities assume local thermodynamic equilibrium (LTE).
- `python_version`: the version of the Python Hyperion library used to generate the file. Set this to '0.8.7' if you are writing files yourself rather than using the Hyperion library.

The datasets present should be the following:

optical_properties

This dataset should consist of a table with the basic optical properties of the dust as a function of frequency, in a binary table. The columns should be:

- `nu`: The frequency, in Hz.
- `albedo`: The albedo of the dust.
- `chi`: The opacity of the dust to extinction, in cm^2/g.
- `P1`, `P2`, `P3`, and `P4`: The four elements of the scattering matrix. These columns should be vector columns, with each table cell containing the elements for as many angles as specified in `scattering_angles`.

scattering_angles

This dataset should consist of a single-column table. The column should be `mu`, and should give the values of the cosine of the scattering angle for which the matrix elements are tabulated in the `Optical properties` dataset.

mean_opacities

This dataset should consist of a table with pre-computed mean opacities for the dust. The columns should be:

- `specific energy`: The specific energy for which the mean opacities are given
- `chi_planck`: The Plank mean opacity to extinction, in cm^2/g
- `chi_rosseland`: The Rosseland mean opacity to extinction, in cm^2/g
- `kappa_planck`: The Plank mean opacity to absorption, in cm^2/g
- `kappa_rosseland`: The Rosseland mean opacity to absorption, in cm^2/g

The temperatures specified should range from 0.1K (or less) to a temperature safely above the maximum temperature expected for the dust in the system.

emissivities

This dataset should consist of a table specifying the emissivities. The columns should be:

- `nu`: The frequencies at which the emissivity is specified.
- `j_nu`: The emissivity for the specified frequency, as a function of specific energy. This should be a vector column, where the width of the column is the number of values specified in the `emissivity_variable` dataset.

emissivity_variable

This dataset should consist of a single-column table. The column should be `specific_energy` and should give the specific energies for which the emissivities are tabulated in the `emissivities` dataset.

4.1.12 Model Input HDF5 Format

Introduction

The radiation transfer code reads in an HDF5 file as input. The contents of the file have to follow a specific layout. To differentiate this format from other HDF5 files, we use the `.rtin` extension for input files to the radiation transfer code.

An `.rtin` file should contain the following four groups:

```
Dust/
Grid/
Sources/
Output/
```

These are described in *Dust*, *Grid*, *Sources*, and *Output* respectively. In addition, a number of attributes should be set at the root level, and these are described in *Root-level attributes*.

Dust

The *Dust* group should contain as many groups (or external/internal links to groups) as dust types. The groups should be named:

```
dust_001/
dust_002/
...
```

Each group should have the layout described in Dust HDF5 Format or should be an external HDF5 link to an actual dust file.

Grid

The **Grid** group should contain two sub-groups, **Geometry**, and **Physics**, which are described below.

Geometry

This group describes the geometry of the model (what type of grid is used, and the position of the cell walls). The group should have an attribute, `grid_type`, giving the type of grid as a string which can be:

- `car`: cartesian grid
- `sph_pol`: spherical polar grid
- `cyl_pol`: cylindrical polar grid
- `amr`: adaptive mesh refinement grid (AMR)
- `oct`: octree grid

The content of the group then depends on the type of grid:

Cartesian (`car`) The **Geometry** group should contain three tabular datasets named `walls_1`, `walls_2`, and `walls_3`, which should each contain one column. The `walls_1` table should contain a column `x` giving the x position of the cell walls as floating point values. Similarly, `walls_2` and `walls_3` should contain one column each, named `y` and `z` respectively, giving the y and z position of the grid cell walls.

Spherical Polar (`sph_pol`) The **Geometry** group should contain three tabular datasets named `walls_1`, `walls_2`, and `walls_3`, which should each contain one column. The `walls_1` table should contain a column `r` giving the radial position of the cell walls as floating point values. Similarly, `walls_2` and `walls_3` should contain one column each, named `t` and `p` respectively, giving the theta and phi position of the grid cell walls.

Cylindrical Polar (`cyl_pol`) The **Geometry** group should contain three tabular datasets named `walls_1`, `walls_2`, and `walls_3`, which should each contain one column. The `walls_1` table should contain a column `w` giving the radial position of the cell walls as floating point values. Similarly, `walls_2` and `walls_3` should contain one column each, named `z` and `p` respectively, giving the z and phi position of the grid cell walls.

AMR (`amr`) The **Geometry** group should contain an attribute `nlevels` giving the number of levels in the grid, as an integer, as well as one sub-group per level. These groups should be formatted as **level_%05d** (i.e. **level_00001**, **level_00002**, etc.) starting at **level_00001**.

Each **level_*** group should then contain an attribute `ngrids` giving the number of grids in the level, as an integer, as well as one sub-group per grid in the level. The sub-groups should be formatted as `grid_%05d` (e.g. **grid_00001**, **grid_00002**) starting at **grid_00001**.

Each **grid_*** group should contain the following attributes:

- `xmin`, `xmax`, `ymin`, `ymax`, `zmin`, `zmax`: the boundaries of the grid, as floating point values.
- `n1`, `n2`, `n3`: the number of cells (not walls) in each direction, as integers.

Octree (`oct`) The **Geometry** group should contain the following attributes:

- `x`, `y`, `z`: the coordinates of the center of the parent cell, as floating point values, in cm
- `dx`, `dy`, `dz`: the size of the parent cell, as floating point values, in cm

In addition, the group should contain a 1-d array representing the `refined` array described in Octree Grids. The array should be given as an integer array instead of a boolean array.

Physics

This group describes the input quantities such as the density and optionally the specific energy of the dust. In all cases where a `density` array should be specified, you may also give a `specific_energy` array with the same dimensions - this can be used as the initial temperature, or can be used as the temperature to use for the images/SED if the number of temperature iterations is set to zero.

Cartesian The **Physics** group should contain a 4-d dataset array named `density` giving the density in c.g.s in each cell. The dimensions of the array should be `(n_dust, n_z, n_y, n_x)`.

Spherical Polar The **Physics** group should contain a 4-d dataset array named `density` giving the density in c.g.s in each cell. The dimensions of the array should be `(n_dust, n_p, n_t, n_r)`.

Cartesian The **Physics** group should contain a 4-d dataset array named `density` giving the density in c.g.s in each cell. The dimensions of the array should be `(n_dust, n_p, n_z, n_w)`.

AMR The **Physics** group should contain a structure similar to that used to represent the geometry. The `nlevels` and `ngrids` attributes are not needed, only the nested **level_*** and **grid_*** groups. Each **grid_*** group should then contain a 4-d dataset array named `density` giving the density in c.g.s in each cell. The dimensions of the array should be `(n_dust, n_z, n_y, n_x)`.

Octree The **Physics** group should contain a 1-d dataset array named `density` giving the density in c.g.s in each cell. Each cell in this array should match a cell in the `refined` array discussed in *Geometry*.

Sources

This should contain one group per source. The name of the groups is not important, and the Python code uses names such as **source_00001**. Each sub-group will contain certain attributes and datasets depending on the source type, as described below.

Common attributes

All sources should have the following attributes:

- `type`: the type of the source, given as a string. This can be `point` (for point sources), `sphere` (for spherical sources), `map` (for diffuse sources), `extern_sph` (for external spherical illumination), `extern_box` (for external illumination from a box), or `plane_parallel` (for a plane-parallel beam).
- `luminosity`: the luminosity of the source, as a floating point value, in c.g.s
- `peeloff`: whether to include the source when computing images with peeling-off, as a string that should be either `yes` or `no`.
- `spectrum`: the type of spectrum to use, as a string. This can be either:
  - `spectrum`, to indicate that a spectrum has been numerically specified. In this case, the group representing the source should also contain a tabular dataset with two columns: `nu`, the frequency in Hz, and `fnu`, the monochromatic flux per frequency (the exact units are not important, because the spectrum is renormalized).
  - `temperature`, to specify that a temperature has been specified. In this case, the temperature should be given as an attribute `temperature`, as a floating-point value.

  - `lte`, to indicate that the source should emit from the dust emissivities in the cell (this is used mainly for diffuse sources). In this case, no addition attributes need to be specified.

Point sources (`point`)

A group representing a point source should contain the following attributes in addition to the *Common attributes* discussed above:

- `x`, `y`, and `z`: the cartesian position of the source, as floating point values, in cm

Spherical sources (`sphere`)

A group representing a spherical source should contain the following attributes in addition to the *Common attributes* discussed above:

- `x`, `y`, and `z`: the cartesian position of the center of the source, as floating-point values, in cm
- `r`: the radius of the sphere, as a floating point value, in cm
- `limb`: whether to include limb darkening, as a string that can be either `yes` or `no`.

Diffuse sources (`map`)

In addition to the *Common attributes* discussed above, a group representing a diffuse source should contain a dataset called `Luminosity map` containing the relative luminosity of each cell as a 3-d array. The dimensions of the grid should be identical to the density grid (see *Grid*).

External spherical sources (`extern_sph`)

A group representing external illumination from a spherical source should contain the following attributes in addition to the *Common attributes* discussed above:

- `x`, `y`, and `z`: the cartesian position of the center of the source, as floating-point values, in cm
- `r`: the radius of the sphere, as a floating point value, in cm

External box sources (`extern_box`)

A group representing external illumination from a box source should contain the following attributes in addition to the *Common attributes* discussed above:

- `xmin`, `xmax`, `ymin`, `ymax`, `zmin`, `zmax`: the lower and upper bounds definining the box, as floating-point values, in cm.

Plane parallel sources (`plane_parallel`)

A group representing a plane-parallel beam source should contain the following attributes in addition to the *Common attributes* discussed above:

- `x`, `y`, and `z`: the cartesian position of the center of the source, as floating-point values, in cm
- `r`: the radius of the sphere, as a floating point value, in cm

- `theta`, `phi`: the 3-d angle giving the direction of the beam in spherical polar coordinates, as floating point values, in degrees.

Output

The `Output` group should have four attributes *output_density*, *output_density_diff*, *output_n_photons*, and *output_specific_energy*, which should be set to a string to indicate whether to output the quantity after the last iteration (`last`), after every iteration (`all`), or never (`none`). The `density_diff` quantity is the density difference compared to the input density (which will be non-zero in cases for example where one uses dust sublimation).

In addition, the `Output` group should contain two sub-groups, `Binned` and `Peeled`, that can be used to specify the parameters of the output images/SEDs. Both groups should always be present, even if they are empty. The content of these groups is described in the following two sections:

Binned

If you want to compute images using binning of escaping photons (not recommended in most cases as it is inefficient and causes angle-averaging of outputs), then set the `n_theta` and `n_phi` parameters, which should be used to indicate, as integers, the number of bins in the theta and phi directions respectively.

Peeled

This group should contain as many sub-groups as image/SED sets you want to compute (the name of the sub-groups is unimportant). Each sub-group should then contain the following attributes:

- `n_view`: the number of viewing angles for the image/SED, given as an integer.
- `compute_image`: whether to compute images, given as a string that can be `yes` or `no`. If this is `yes`, then the following attributes should also be specified:
  - `n_x` and `n_y`: the dimensions of the image, as integers
  - `x_min`, `x_max`, `y_min`, and `y_max`: the lower and upper bounds of the image as floating point values, in cm
- `compute_sed`: whether to compute SEDs, given as a string that can be `yes` or `no`. If this is `yes`, then the following attributes should also be specified:
  - `n_ap`: the number of apertures to compute the SED for
  - `ap_min`, `ap_max`: the smallest and largest apertures to use. If `n_ap` is 1, then `ap_min` should be the same as `ap_max`.
- `track_origin`: indicates whether the origin of the photon (e.g. emission vs scattering, or which source it originated from) should be retained in the output image. This can be:
  - `no`: no photon tracking is done
  - `basic`: photons are split into ones emitted or scattered, and whether they were last emitted from a source or from the dust.
  - `detailed`: as for `basic`, but also keeping the ID of the source or dust population last emitted from.
  - `scatterings`: photons are split into ones emmitted by sources or dust, and split by the number of times they scatter.
- `track_n_scat`: an integer giving the maximum number of scatterings to record if `track_origin` is set to `scatterings`.

- uncertainties: whether to compute and output uncertainties on the images and/or SEDs. This should be specified as a string that can be yes or no.
- n_wav: the number of wavelengths/frequencies to compute the images and/or SEDs for.
  - If using monochromatic radiative transfer, then the minimum and maximum frequency of the image and/or SED should be specified with two attributes inu_min and inu_max, which should be given as integers giving the indices to the frequencies array (the first array element should be 1).
  - If not using monochromatic radiative transfer, then the minimum and maximum wavelengths of the image and/or SED should be specified with two attributes wav_min and wav_max, which should be given as floating point values, in microns.
- d_min and d_max: these give the minimum and maxium depth within which to use photons for the image/SED. Unless you need this and understand the implications, you should set this to -inf and +inf respectively if inside_observer is no, and 0 and +inf respectively if inside_observer is yes.
- inside_observer: whether to compute the image from an observer located inside the grid, or from an observer at infinity. This should be given as a string that can be either yes or no. In most cases you will likely want to use no.
- ignore_optical_depth: whether to ignore optical depth effects when computing the image/SED. This should be given as a string that can be either yes or no, and should be set to no in most cases. This can be useful for debugging and for understanding how much optical depth effects are affecting an image or SED.
- If inside_observer is yes, then the position of the observer should be given with the observer_x, observer_y, and observer_z attributes, as floating point values, in cm.
- If inside_observer is no, then the origin for the peeling-off should be given with the peeloff_x, peeloff_y, and peeloff_z attributes, as floating point values, in cm. In most cases, these should be set to zero.

In addition, the group should contain a table dataset with two columns, theta and phi, giving the viewing angles as floating point values, in degrees.

Root-level attributes

The overall configuration for the model should be specified as attributes for the root group in the HDF5 file. The parameters needed are described in the following sub-sections.

General

- python_version: the version of the Hyperion Python library used to generate the file. If you are not generating the file with the Hyperion Python library (which is probably the case if you are reading this page) then set it to '0.8.7' since that is the version for which the format in this page is described.
- physics_io_bytes: whether to write out the physical quantities using 4- or 8-byte floating point values. Should be either 4 or 8 (integer).

Iterations

- n_lucy_iter: Number of temperature-calculating Lucy iterations (integer)
- check_convergence: Whether to check for convergence in the specific energy calculation. Should be yes or no (string).
- convergence_absolute: the threshold for absolute changes in the specific energy (float).

- `convergence_relative`: the threshold for relative changes in the specific energy (float).
- `convergence_percentile`: the percentile at which to check the absolute and relative changes in the specific energy (float).

See *Specific energy calculation* for the latter three.

Diffusion approximation

- `mrw`: Whether or not to use the modified random walk (MRW) algorithm. Should be `yes` or `no` (string).
- `pda`: Whether or not to use the partial diffusion approximation (PDA) algorithm. Should be `yes` or `no` (string).

If `mrw` is `yes`, the following two attributes should be set:

- `mrw_gamma`: The gamma parameter for the modified random walk as described in *Diffusion* (float).
- `n_inter_mrw_max`: The maximum number of MRW interactions before a photon is killed (integer).

Images/SEDs

- `raytracing`: Whether to do a raytracing iteration at the end of the calculation. Should be `yes` or `no` (string).
- `monochromatic`: Whether to calculate the images/SEDs in monochromatic mode. Should be `yes` or `no` (string).

Number of photons

The following attributes are required:

- `n_stats`: how often to display performance stats. For the MPI-enabled code, this also determines the chunk of photons to dispatch to each thread at a time (integer).

If `n_initial_iter` is non-zero, then the following photon number should be specified:

- `n_initial_photons`: number of photons to emit per iteration in the initial iterations (integer).

If `raytracing` is `yes`, then the following photon numbers should be specified:

- `n_ray_photons_sources`: number of raytracing photons from sources (integer). Does not need to be specified if there are no sources.
- `n_ray_photons_dust`: number of raytracing photons from dust (integer). Does not need to be specified if there are no dust density grids.

If `monochromatic` is `yes`, then the following photon numbers should be specified:

- `n_last_photons_sources`: the number of photons (per frequency) to emit from sources in the imaging iteration (integer). Does not need to be specified if there are no sources.
- `n_last_photons_dust`: the number of photons (per frequency) to emit from dust in the imaging iteration (integer). Does not need to be specified if there are no dust density grids.

Miscellaneous

- `forced_first_scattering`: whether to use the forced first scattering algorithm. Should be one of `yes` or `no` (string).

- `kill_on_absorb`: whether to kill photons when they are absorbed rather than re-emitting them (useful for scattering-only calculations). Should be one of `yes` or `no` (string).
- `n_inter_max`: the maximum number of interactions a photon can have before being it is killed (integer).
- `n_reabs_max`: the maximum number of times a photon can be re-absorbed before it is killed (integer).

Optional

The following attributes are optional:

- `sample_sources_evenly`: whether to emit the same number of photons from each source (as opposed to emitting a number of photons proportional to the luminosity). Should be `yes` or `no` (string). Defaults to `no`.
- `enforce_energy_range`: whether to always reset values below the minimum and above the maximum specific energy to the bounds of the range. Should be `yes` or `no` (string). Defaults to `yes`.

4.2 Detailed description of objects and functions (API)

4.2.1 Utilities

hyperion.util.constants

The `hyperion.util.constants` module contains a number of useful physical constants that can be used when setting up or postprocessing models. All constants are defined in the cgs system. Since all attributes for objects (sources, images, etc.) required parameters to be specified in the cgs system, one can therefore do:

```
from hyperion.util.constants import au, pc
e = m.add_power_law_envelope()
e.rmin = 0.1 * au
e.rmax = pc
```

which is equivalent to writing:

```
e = m.add_power_law_envelope()
e.rmin = 1.49598e12
e.rmax = 3.08568025e18
```

but the former is more readable. The available constants are described below:

Fundamental constants

`hyperion.util.constants.`**`h = 6.626068e-27`**
Planck constant (erg.s)

`hyperion.util.constants.`**`k = 1.3806503e-16`**
Boltzmann constant (erg/K)

`hyperion.util.constants.`**`c = 29979245800.0`**
Speed of light (cm/s)

`hyperion.util.constants.`**`G = 6.673e-08`**
Gravitational constant (cm^3/g/s^2)

`hyperion.util.constants.`**`sigma = 5.67051e-05`**
Stefan-Boltzmann constant (erg/cm^2/K^4/s)

hyperion.util.constants.**m_h = 1.6733e-24**
Mass of a hydrogen atom (g)

Solar constants

hyperion.util.constants.**lsun = 3.846e+33**
Luminosity of the Sun (erg/s)

hyperion.util.constants.**msun = 1.989e+33**
Mass of the Sun (g)

hyperion.util.constants.**rsun = 69550800000.0**
Radius of the Sun (cm)

hyperion.util.constants.**tsun = 5778.0**
Effective temperature of the Sun (K)

Common Astronomical constants

hyperion.util.constants.**au = 14959800000000.0**
One Astronomical Unit (cm)

hyperion.util.constants.**pc = 3.08568025e+18**
One parsec (cm)

hyperion.util.constants.**kpc = 3.08568025e+21**
One kiloparsec (cm)

hyperion.util.constants.**year = 31557600.0**
Length of a year (s)

4.2.2 Models

hyperion.model.Model

class hyperion.model.**Model**(*name=None*)

Adding sources

Setting the grid

Setting quantities

Images/SEDs

Configuration

Running

Using grids from files

Re-using previous models

Methods (detail)

add_source(*source*)

add_point_source(**args*, ***kwargs*)

add_spherical_source(**args*, ***kwargs*)

add_external_spherical_source(**args*, ***kwargs*)

add_external_box_source(**args*, ***kwargs*)

add_map_source(**args*, ***kwargs*)

add_plane_parallel_source(**args*, ***kwargs*)

set_grid(*grid*)

set_cartesian_grid(*x_wall*, *y_wall*, *z_wall*)

set_cylindrical_polar_grid(*w_wall*, *z_wall*, *p_wall*)

set_spherical_polar_grid(*r_wall*, *t_wall*, *p_wall*)

set_octree_grid(*x*, *y*, *z*, *dx*, *dy*, *dz*, *refined*)

set_amr_grid(*description*)

add_density_grid(*density*, *dust*, *specific_energy=None*, *merge_if_possible=False*)

Add a density grid to the model

Parameters **density** : np.ndarray or grid quantity

The density of the dust. This can be specified either as a 3-d Numpy array for cartesian, cylindrical polar, or spherical polar grids, as a 1-d array for octree grids, or as a grid quantity object for all grid types. Grid quantity objects are obtained by taking an instance of a grid class (e.g. `AMRGrid`, `CartesianGrid`, ...) and specifying the quantity as an index, e.g. `amr['density']` where `amr` is an `AMRGrid` object.

dust : str or dust instance

The dust properties, specified either as a string giving the filename of the dust properties, or a as an instance of a dust class (e.g. `SphericalDust`, `IsotropicDust`, ...).

specific_energy : np.ndarray or grid quantity, optional

The specific energy of the density grid. Note that in order for this to be useful, the number of initial iterations should be set to zero, otherwise these values will be overwritten after the first initial iteration.

merge_if_possible : bool

Whether to merge density arrays that have the same dust type

add_peeled_images(*sed=True*, *image=True*)

Define a set of (peeled) images/SEDs.

This returns a *PeeledImageConf* instance that can be used to set the image/SED parameters.

Parameters **sed** : bool, optional

Whether to compute a set of SEDs

image : bool, optional

Whether to compute a set of images

Returns **image_conf** : *PeeledImageConf* instance

Instance that can be used to set the image/SED parameters

Examples

```
>>> image = m.add_peeled_images(sed=False, image=True)
>>> image.set_wavelength_range(250, 0.01, 1000.)
>>> ...
```

add_binned_images(*sed=True*, *image=True*)

Define a set of (binned) images/SEDs.

This returns a *BinnedImageConf* instance that can be used to set the image/SED parameters.

Parameters **sed** : bool, optional

Whether to compute a set of SEDs

image : bool, optional

Whether to compute a set of images

Returns **image_conf** : *BinnedImageConf* instance

Instance that can be used to set the image/SED parameters

Examples

```
>>> image = m.add_binned_images(sed=False, image=True)
>>> image.set_wavelength_range(250, 0.01, 1000.)
>>> ...
```

set_seed(*seed*)

Set the seed for the random number generation

Parameters **seed** : int

The seed with which to initialize the random number generation. This should be negative.

set_propagation_check_frequency (*frequency*)
Set how often to check that the photon is in the right cell

During photon propagation, it is possible that floating point issues cause a photon to end up in the wrong cell. By default, the code will randomly double check the position and cell of a photon for every 1 in 1000 cell wall crossings, but this can be adjusted with this method. Note that values higher than around 0.001 will cause the code to slow down.

Parameters **frequency** : float

How often the photon position and cell should be double-checked (1 is always, 0 is never).

set_monochromatic (*monochromatic*, *wavelengths=None*, *frequencies=None*)
Set whether to do the radiation transfer at specific wavelengths.

Parameters **monochromatic** : bool

Whether to carry out radiation transfer at specific frequencies or wavelengths

wavelengths : iterable of floats, optional

The wavelengths to compute the radiation transfer for, in microns

If 'monochromatic' is True then 'wavelengths' is required :

set_minimum_temperature (*temperature*)
Set the minimum temperature for the dust

Parameters **temperature** : float, list, tuple, or Numpy array

Notes

This method should not be used in conjunction with `set_minimum_specific_energy` - only one of the two should be used.

set_minimum_specific_energy (*specific_energy*)
Set the minimum specific energy for the dust

Parameters **specific_energy** : float, list, tuple, or Numpy array

Notes

This method should not be used in conjunction with `set_minimum_temperature` - only one of the two should be used.

set_specific_energy_type (*specific_energy_type*)
Set whether to use the specific specific energy as an initial value or an additional component at each iteration.

This only has an effect if a specific energy was specified during `add_density_grid`.

Parameters **specific_energy_type** : str

Can be `'initial'` (use only as initial value) or `'additional'` (add at every iteration)

set_n_initial_iterations (*n_iter*)
Set the number of initial iterations for computing the specific energy in each cell.

Parameters **n_iter** : int

The number of initial iterations

set_raytracing(*raytracing*)
Set whether to use raytracing for the non-scattered flux

If enabled, only scattered photons are peeled off in the iteration following the initial iterations, and an additional final iteration is carrried out, with raytracing of the remaining flux (sources and thermal and non-thermal dust emission).

Parameters **raytracing** : bool

Whether or not to use raytracing in the final iteration

set_max_interactions(*inter_max*, *warn=True*)
Set the maximum number of interactions a photon can have.

Parameters **inter_max** : int

Maximum number of interactions for a single photon. This can be used to prevent photons from getting stuck in very optically thick regions, especially if the modified random walk is not used.

warn : bool, optional

Whether to emit a warning whenever photons are killed for exceeding the maximum number of iterations.

set_max_reabsorptions(*reabs_max*, *warn=True*)
Set the maximum number of successive reabsorptions by a source that a photon can have.

Parameters **reabs_max** : int

Maximum number of reabsorptions for a single photon.

warn : bool, optional

Whether to emit a warning whenever photons are killed for exceeding the maximum number of reabsorptions.

set_pda(*pda*)
Set whether to use the Partial Diffusion Approximation (PDA)

If enabled, the PDA is used to compute the specific energy in cells which have seen few or no photons by formally solving the diffusion equations, using the cells with valid specific energies as boundary conditions.

Parameters **pda** : bool

Whether or not to use the PDA

References

Min et al. 2009, Astronomy and Astrophysics, 497, 155

set_mrw(*mrw*, *gamma=1.0*, *inter_max=1000*, *warn=True*)
Set whether to use the Modified Random Walk (MRW) approximation

If enabled, the MRW speeds up the propagation of photons in very optically thick regions by locally setting up a spherical diffusion region.

Parameters **mrw** : bool

Whether or not to use the MRW

gamma : float, optional

The parameter describing the starting criterion for the MRW. The MRW is carried out if the distance to the closest cell is larger than *gamma* times the Rosseland mean free path.

inter_max : int, optional

Maximum number of interactions during a single random walk. This can be used to prevent photons from getting stuck in the corners of cells in very optically thick regions, where the MRW stars to become inefficient itself.

warn : bool, optional

Whether to emit a warning whenever photons are killed for exceeding the maximum number of mrw steps.

References

Min et al. 2009, Astronomy and Astrophysics, 497, 155

set_convergence(*convergence*, *percentile=100.0*, *absolute=0.0*, *relative=0.0*)
Set whether to check for convergence over the initial iterations

If enabled, the code will check whether the specific energy absorbed in each cell has converged. First, the ratio between the previous and current specific energy absorbed in each cell is computed in each cell, and the value at the specified percentile (*percentile*) is found. Then, convergence has been achieved if this value is less than an absolute threshold (*absolute*), and if it changed by less than a relative threshold ratio (*relative*).

Parameters **convergence** : bool

Whether or not to check for convergence.

percentile : float, optional

The percentile at which to check for convergence.

absolute : float, optional

The abolute threshold below which the percentile value of the ratio has to be for convergence.

relative : float, optional

The relative threshold below which the ratio in the percentile value has to be for convergence.

set_kill_on_absorb(*kill_on_absorb*)
Set whether to kill absorbed photons

Parameters **kill_on_absorb** : bool

Whether to kill absorbed photons

set_forced_first_scattering(*forced_first_scattering*)
Set whether to ensure that photons scatter at least once before escaping the grid.

Parameters **forced_first_scattering** : bool

Whether to force at least one scattering before escaping the grid

References

Wood & Reynolds, 1999, The Astrophysical Journal, 525, 799

set_output_bytes(*io_bytes*)
Set whether to output physical quantity arrays in 32-bit or 64-bit

Parameters **io_bytes** : int

The number of bytes for the output. This should be either 4 (for 32-bit) or 8 (for 64-bit).

set_sample_sources_evenly(*sample_sources_evenly*)
If set to 'True', sample evenly from all sources and apply probability weight based on relative luminosities. Otherwise, sample equal energy photons from sources with probability given by relative luminosities.

Parameters **sample_evenly** : bool

Whether to sample different sources evenly

set_enforce_energy_range(*enforce*)
Set how to deal with cells that have specific energy rates that are below or above that provided in the mean opacities and emissivities.

Parameters **enforce** : bool

Whether or not to reset specific energies that are above or below the range of values used to specify the mean opacities and emissivities to the maximum or minimum value of the range. Setting this to True modifies the energy in the simulation, but ensures that the emissivities are consistent with the energy in the cells. Setting this to False means that the total energy in the grid will be correct, but that the emissivities may be inconsistent with the energy in the cells (if an energy is out of range, the code will pick the closest available one). In both cases, warnings will be displayed to notify the user whether this is happening.

set_copy_input(*copy*)
Set whether to copy the input data into the output file.

Parameters **copy** : bool

Whether to copy the input data into the output file (True) or whether to link to it (False)

write(*filename=None*, *compression=True*, *copy=True*, *absolute_paths=False*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*, *overwrite=True*)
Write the model input parameters to an HDF5 file

Parameters **filename** : str

The name of the input file to write. If no name is specified, the filename is constructed from the model name.

compression : bool

Whether to compress the datasets inside the HDF5 file.

copy : bool

Whether to copy all external content into the input file, or whether to just link to external content.

absolute_paths : bool

If copy=False, then if absolute_paths is True, absolute filenames are used in the link, otherwise the path relative to the input file is used.

wall_dtype : type

Numerical type to use for wall positions.

physics_dtype : type

Numerical type to use for physical grids.

overwrite : bool

Whether to overwrite any pre-existing file

run (*filename=None*, *logfile=None*, *mpi=False*, *n_processes=4*, *overwrite=False*)
Run the model (should be called after *write()*).

Parameters **filename** : str, optional

The output filename for the model. If not specified, then if the input file name contains `.rtin`, then this is replaced with `.rtout`, and otherwise `.rtout` is appended to the input filename.

logfile : str, optional

If specified, the standard output and errors will be output to this log file

mpi : bool, optional

Whether to run the model using the parallel (MPI) version of Hyperion.

n_processes : int, optional

If `mpi` is set to `True`, this can be used to specify the number of processes to run Hyperion on.

overwrite : bool, optional

If set to `True`, the output file is overwritten without warning.

use_grid_from_file (*filename*, *path='/'*, *dust=[]*)
Use a grid from disk and don't read it in.

Parameters **filename** : str

The name of the file to read from

path : str, optional

The path where the grid is located inside the file

dust : list, optional

A list containing a dust file or object for each dust index in the grid

classmethod read (*filename*, *only_initial=True*)
Read in a previous model file

This can be used to read in a previous input file, or the input in an output file (which is possible because the input to a model is stored or linked in an output file).

If you are interested in re-using the final specific energy (and final density, if present) of a previously run model, you can use:

```
>>> m = Model.read('previous_model.rtout', only_initial=False)
```

Parameters **filename** : str

The name of the file to read the input data from

only_initial : bool, optional

Whether to use only the initial quantities, or whether the final specific energy (and optionally density) from the previous model can be used. By default, only the input density (and specific energy, if present) are read in.

use_geometry (*filename*)
Use the grid from an existing output or input file

Parameters **filename** : str

The file to read the grid from. This can be either the input or output file from a radiation transfer run.

use_quantities (*filename, quantities=['density', 'specific_energy'], use_minimum_specific_energy=True, use_dust=True, copy=True, only_initial=False*)
Use physical quantities from an existing output file

Parameters **filename** : str

The file to read the quantities from. This should be the output file of a radiation transfer run.

quantities : list

Which physical quantities to read in. Can include 'density' and 'specific_energy'.

copy : bool

Whether to copy the quantities into the new input file, or whether to just link to them.

use_minimum_specific_energy : bool

Whether to also use the minimum specific energy values from the file specified

use_dust : bool

Whether to also use the dust properties from the file specified

copy : bool

Whether to read in a copy of the data. If set to False, then the physical quantities will only be links to the specified HDF5 file, and can therefore not be modified.

only_initial : bool, optional

Whether to use only the initial quantities, or whether the final specific energy (and optionally density) from the previous model can be used. By default, only the input density (and specific energy, if present) are read in.

use_sources (*filename*)
Use sources from an existing output file

Parameters **filename** : str

The file to read the sources from. This should be the input or output file of a radiation transfer run.

use_image_config (*filename*)
Use image configuration from an existing output or input file

Parameters **filename** : str

The file to read the parameters from. This can be either the input or output file from a radiation transfer run.

use_run_config (*filename*)
Use runtime configuration from an existing output or input file

Parameters **filename** : str

The file to read the parameters from. This can be either the input or output file from a radiation transfer run.

use_output_config (*filename*)
Use output configuration from an existing output or input file

Parameters **filename** : str

The file to read the parameters from. This can be either the input or output file from a radiation transfer run.

hyperion.model.AnalyticalYSOModel

AnalyticalYSOModel inherits from *Model*, so all methods and attributes present in the latter can be used with the former, but they are not listed here.

class hyperion.model.**AnalyticalYSOModel**(*name=None*)

Adding density structures

Setting the grid automatically

Miscellaneous

Writing

Methods (detail)

add_flared_disk()
Add a flared disk to the model

Returns **disk** : *FlaredDisk*

A *FlaredDisk* instance.

Examples

To add a flared disk to the model, you can do:

```
>>> disk = m.add_flared_disk()
```

then set the disk properties using e.g.:

```
>>> disk.mass = 1.e30  # g
>>> disk.rmin = 1e10  # cm
>>> disk.rmax = 1e14  # cm
```

See the *FlaredDisk* documentation to see which parameters can be set.

add_alpha_disk()
Add an alpha disk to the geometry

This is similar to a flared disk, but with accretion luminosity. See *AlphaDisk* for more details.

Returns **disk** : *AlphaDisk*

A *AlphaDisk* instance.

Examples

To add an alpha disk to the model, you can do:

```
>>> disk = m.add_alpha_disk()
```

then set the disk properties using e.g.:

```
>>> disk.mass = 1.e30  # g
>>> disk.rmin = 1e10  # cm
>>> disk.rmax = 1e14  # cm
```

See the *AlphaDisk* documentation to see which parameters can be set.

add_power_law_envelope()
Add a spherically symmetric power-law envelope to the model

Returns **env** : *PowerLawEnvelope*

A *PowerLawEnvelope* instance.

Examples

To add a power-law envelope to the model, you can do:

```
>>> env = m.add_power_law_envelope()
```

then set the envelope properties using e.g.:

```
>>> from hyperion.util.constants import msun, au
>>> env.mass = 0.1 * msun  # g/s
>>> env.rmin = 0.1 * au  # cm
>>> env.rmax = 10000. * au  # cm
```

See the *PowerLawEnvelope* documentation to see which parameters can be set.

add_ulrich_envelope()
Add an infalling rotationally flatted envelope to the model

Returns **env** : *UlrichEnvelope*

An *UlrichEnvelope* instance.

Examples

To add an infalling envelope to the model, you can do:

```
>>> env = m.add_ulrich_envelope()
```

then set the envelope properties using e.g.:

```
>>> from hyperion.util.constants import msun, yr, au
>>> env.mdot = 1.e-6 * msun / yr  # g/s
>>> env.rmin = 0.1 * au  # cm
>>> env.rmax = 10000. * au  # cm
```

See the *UlrichEnvelope* documentation to see which parameters can be set.

add_ambient_medium(*subtract=[]*)
Add an ambient density medium to the model

Parameters **subtract** : list

Components to subtract from the ambient density medium (see notes below).

Returns **ambient** : *AmbientMedium*

An *AmbientMedium* instance.

Notes

By default, the ambient medium simply adds a constant density `rho` of dust to the whole model between the inner and outer radius. However, it is possible to pass components that should be subtracted from the constant density using the `subtract=` argument. In the following example:

```
>>> e = m.add_power_law_envelope()
>>> m.add_ambient_medium(subtract=[e])
```

the ambient medium does not simply add a constant density `rho` of dust everywhere, but it adds dust such that the density never falls below `rho` between `rmin` and `rmax` - that is, it subtracts the density of component `e` from the `rho`, with a minimum of zero. In regions where the density of component of `e` is larger than `rho`, no dust is added.

Examples

To add an ambient medium to the model, you can do:

```
>>> ambient = m.add_ambient_medium()
```

then set the ambient medium properties using e.g.:

```
>>> from hyperion.util.constants import au, pc
>>> ambient.rho = 1.e-20  # cgs
>>> ambient.rmin = 0.1 * au  # cm
>>> ambient.rmax = pc  # cm
```

See the *AmbientMedium* documentation to see which parameters can be set.

set_spherical_polar_grid_auto(*n_r*, *n_theta*, *n_phi*, *rmax=None*, *min_spacing=1e-08*)
Set the grid to be spherical polar with automated resolution.

Parameters **n_r, n_theta, n_phi** : int

Number of cells to use in the radial, theta, and azimuthal directions.

rmax : float, optional

The maximum radius to extend out to. If not specified, this is set to the maximum spherical radius of the dust geometry in the mid-plane. Note that if you are including a disk with a cylindrical outer edge, this should be set to a value larger than the disk radius, otherwise the disk will be truncated with a spherical edge.

min_spacing : float, optional

The minimum spacing (in relative terms) for the inner cell walls. The spacing from rmin to the next cell wall cannot be smaller than rmin * (1 + min_spacing).

set_cylindrical_polar_grid_auto (*n_w*, *n_z*, *n_phi*, *wmin=None*, *wmax=None*, *zmin=None*, *zmax=None*, *min_spacing=1e-08*)

Set the grid to be cylindrical polar with automated resolution.

Parameters **n_w, n_z, n_phi** : int

Number of cells to use in the radial, vertical, and azimuthal directions.

wmax : float, optional

The maximum radius to extend out to. If not specified, this is set to the maximum cylindrical radius of the dust geometry in the mid-plane.

zmax : float, optional

The maximum height above and below the midplane to extend to. If not specified, this is set to the maximum cylindrical radius of the dust geometry.

min_spacing : float, optional

The minimum spacing (in relative terms) for the inner cell walls. The spacing from rmin to the next cell wall cannot be smaller than rmin * (1 + min_spacing).

setup_magnetospheric_accretion (*mdot*, *rtrunc*, *fspot*, *xwav_min=0.001*, *xwav_max=0.01*)

Set up the model for magnetospheric accretion

Parameters **mdot** : float

The accretion rate onto the star in cgs

rtrunc : float

The magnetospheric truncation radius of the disk in cgs

fspot : float

The spot coverage fraction. Photons will be emitted uniformly from the star, the coverage fraction `fspot` will determine the spectrum of the hot spot emission (smaller covering fractions will lead to a hotter spectrum).

Notes

This method only takes into account the hot spot and X-ray emission from the stellar surface. To simulate the viscous accretion luminosity in the disk, add an *AlphaDisk* to the model using *add_alpha_disk()* and set the accretion rate or luminosity accordingly.

write (*filename=None*, *compression=True*, *copy=True*, *absolute_paths=False*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*, *overwrite=True*, *merge_if_possible=True*)

Write the model input parameters to an HDF5 file

Parameters **filename** : str

The name of the input file to write. If no name is specified, the filename is constructed from the model name.

compression : bool

Whether to compress the datasets inside the HDF5 file.

copy : bool

Whether to copy all external content into the input file, or whether to just link to external content.

absolute_paths : bool

If copy=False, then if absolute_paths is True, absolute filenames are used in the link, otherwise the path relative to the input file is used.

wall_dtype : type

Numerical type to use for wall positions.

physics_dtype : type

Numerical type to use for physical grids.

overwrite : bool

Whether to overwrite any pre-existing file

merge_if_possible : bool

Whether to merge density arrays that have the same dust type

hyperion.model.ModelOutput

class `hyperion.model.`**`ModelOutput`**(*filename*)

A class that can be used to access data in the output file from radiative transfer models.

Parameters **name** : str

The name of the model output file (including extension)

Methods

Methods (detail)

`get_sed`(*stokes='I'*, *group=0*, *technique='peeled'*, *distance=None*, *component='total'*, *inclination='all'*, *aperture='all'*, *uncertainties=False*, *units=None*, *source_id=None*, *dust_id=None*, *n_scat=None*)

Retrieve SEDs for a specific image group and Stokes component.

Parameters **stokes** : str, optional

The Stokes component to return. This can be:

- 'I': Total intensity [default]
- 'Q': Q Stokes parameter (linear polarization)

- 'U': U Stokes parameter (linear polarization)
- 'V': V Stokes parameter (circular polarization)
- 'linpol': Total linear polarization fraction
- 'circpol': Total circular polariation fraction

Note that if the SED was set up with `set_stokes(False)`, then only the `I` component is available.

technique : str, optional

Whether to retrieve SED(s) computed with photon peeling-off ('peeled') or binning ('binned'). Default is 'peeled'.

group : int, optional

The peeloff group (zero-based). If multiple peeloff image groups were requested, this can be used to select between them. The default is to return the first group. This option is only used if technique='peeled'.

distance : float, optional

The distance to the observer, in cm.

component : str, optional

The component to return based on origin and last interaction. This can be:

- 'total': Total flux
- 'source_emit': The photons were last emitted from a source and did not undergo any subsequent interactions.
- 'dust_emit': The photons were last emitted dust and did not undergo any subsequent interactions
- 'source_scat': The photons were last emitted from a source and were subsequently scattered
- 'dust_scat': The photons were last emitted from dust and were subsequently scattered
- 'source': The photons that were last emitted from a source
- 'dust': The photons that were last emitted from dust

aperture : int, optional

The index of the aperture to plot (zero-based). Use 'all' to return all apertures, and -1 to show the largest aperture.

inclination : int, optional

The index of the viewing angle to plot (zero-based). Use 'all' to return all viewing angles.

uncertainties : bool, optional

Whether to compute and return uncertainties

units : str, optional

The output units for the SED(s). Valid options if a distance is specified are:

- `'ergs/cm^2/s'`
- `'ergs/cm^2/s/Hz'`

- `'Jy'`
- `'mJy'`

The default is `'ergs/cm^2/s'`. If a distance is not specified, then this option is ignored, and the output units are ergs/s.

source_id, dust_id : int or str, optional

If the output file was made with track_origin='detailed', a specific source and dust component can be specified (where 0 is the first source or dust type). If 'all' is specified, then all components are returned individually. If neither of these are not specified, then the total component requested for all sources or dust types is returned. For sources, it is also possible to specify a source name as a string, if the source name was set during the set-up.

n_scat : int, optional

If the output file was made with track_origin='scatterings', the number of scatterings can be specified here. If specified, the image is constructed only from photons that have scattered `n_scat` times since being last emitted.

Returns wav : numpy.ndarray

The wavelengths for which the SEDs are defined, in microns

flux or degree of polarization : numpy.ndarray

The flux or degree of polarization. This is a data cube which has at most three dimensions (n_inclinations, n_apertures, n_wavelengths). If an aperture or inclination is specified, this reduces the number of dimensions in the flux cube. If *stokes* is one of 'I', 'Q', 'U', or 'V', the flux is either returned in ergs/s (if distance is not specified) or in the units specified by units= (if distance is specified). If *stokes* is one of 'linpol' or 'circpol', the degree of polarization is returned as a fraction in the range 0 to 1.

uncertainty : numpy.ndarray

The uncertainties on the flux or degree of polarization. This has the same dimensions as the flux or degree of polarization array. This is only returned if uncertainties were requested.

get_image(*stokes='I'*, *group=0*, *technique='peeled'*, *distance=None*, *component='total'*, *inclination='all'*, *uncertainties=False*, *units=None*, *source_id=None*, *dust_id=None*, *n_scat=None*)

Retrieve images for a specific image group and Stokes component.

Parameters stokes : str, optional

The Stokes component to return. This can be:

- 'I': Total intensity [default]
- 'Q': Q Stokes parameter (linear polarization)
- 'U': U Stokes parameter (linear polarization)
- 'V': V Stokes parameter (circular polarization)
- 'linpol': Total linear polarization fraction
- 'circpol': Total circular polariation fraction

Note that if the image was set up with `set_stokes(False)`, then only the `I` component is available.

technique : str, optional

Whether to retrieve an image computed with photon peeling-off ('peeled') or binning ('binned'). Default is 'peeled'.

group : int, optional

The peeloff group (zero-based). If multiple peeloff image groups were requested, this can be used to select between them. The default is to return the first group. This option is only used if technique='peeled'.

distance : float, optional

The distance to the observer, in cm.

component : str, optional

The component to return based on origin and last interaction. This can be:

- 'total': Total flux
- 'source_emit': The photons were last emitted from a source and did not undergo any subsequent interactions.
- 'dust_emit': The photons were last emitted dust and did not undergo any subsequent interactions
- 'source_scat': The photons were last emitted from a source and were subsequently scattered
- 'dust_scat': The photons were last emitted from dust and were subsequently scattered
- 'source': The photons that were last emitted from a source
- 'dust': The photons that were last emitted from dust

inclination : int, optional

The index of the viewing angle to plot (zero-based). Use 'all' to return all viewing angles.

uncertainties : bool, optional

Whether to compute and return uncertainties

units : str, optional

The output units for the image(s). Valid options if a distance is specified are:

- `'ergs/cm^2/s'`
- `'ergs/cm^2/s/Hz'`
- `'Jy'`
- `'mJy'`
- `'MJy/sr'`

The default is `'ergs/cm^2/s'`. If a distance is not specified, then this option is ignored, and the output units are ergs/s.

source_id, dust_id : int or str, optional

If the output file was made with track_origin='detailed', a specific source and dust component can be specified (where 0 is the first source or dust type). If 'all' is specified, then all components are returned individually. If neither of these are not specified, then the total component requested for all sources or dust types is returned. For sources, it is

also possible to specify a source name as a string, if the source name was set during the set-up.

n_scat : int, optional

If the output file was made with track_origin='scatterings', the number of scatterings can be specified here. If specified, the image is constructed only from photons that have scattered `n_scat` times since being last emitted.

Returns **wav** : numpy.ndarray

The wavelengths for which the SEDs are defined, in microns

flux or degree of polarization : numpy.ndarray

The flux or degree of polarization. This is a data cube which has at most three dimensions (n_inclinations, n_wavelengths). If an aperture or inclination is specified, this reduces the number of dimensions in the flux cube. If *stokes* is one of 'I', 'Q', 'U', or 'V', the flux is either returned in ergs/s (if distance is not specified) or in the units specified by units= (if distance is specified). If *stokes* is one of 'linpol' or 'circpol', the degree of polarization is returned as a fraction in the range 0 to 1.

uncertainty : numpy.ndarray

The uncertainties on the flux or degree of polarization. This has the same dimensions as the flux or degree of polarization array. This is only returned if uncertainties were requested.

get_quantities(*iteration=-1*)

Retrieve one of the physical grids for the model

Parameters **iteration** : integer, optional

The iteration to retrieve the quantities for. The default is to return the grid for the last iteration.

Returns **grid** : Grid instance

An object containing information about the geometry and quantities

get_available_sources()

Find out what sources are available in the output image (useful if detailed tracking was used)

hyperion.model.helpers

hyperion.model.helpers.**run_with_vertical_hseq**(*prefix*, *model*, *n_iter=10*, *mpi=False*, *n_processes=4*, *overwrite=False*)

Run a model with vertical hydrostatic equilibrium.

Note: this is an experimental function that is currently in development. Please use with care!

The hydrostatic equilibrium condition is only applied to the disk components. The following requirements must be met:

- The model should be an AnalyticalYSOModel
- The model should be defined on a cylindrical polar grid
- The stellar mass should be set
- The model should include at least one disk

The dust properties for the model can be specified as dust or dust+gas densities as this does not have an impact on this calculation - however, the hydrostatic equilibrium is computed assuming an H2 + He mix of gas (i.e. mu=2.279). Note that this calculation also ignores the effects of self-gravity in the disk, which might be important for more massive disks.

Parameters **prefix** : str

The prefix for the output

model : *~hyperion.model.analytical_yso_model.AnalyticalYSOModel*

The model to run

n_iter : int, optional

The number of iterations to run the model for

mpi : bool, optional

Whether to run the model in parallel

n_processes : int, optional

The number of processes to use if `mpi` is `True`

overwrite : bool, optional

Whether to overwrite previous files

`hyperion.model.helpers.`**`tau_to_radius`**(*model*, *tau*, *wav*)

Given a Model instance with a spherical polar coordinate grid, find the radius from which the optical depth to escape radially is a fixed value.

This only works for spherical polar grids, but works for 1-, 2-, and 3-d grids.

Parameters **model** : *~hyperion.model.Model* instance

tau : float

The optical depth for which to find the surface

wav : float

The wavelength at which the optical depth is defined

Returns **r** : np.ndarray

The radius or radii at which the optical depth to escape radially is `tau` at `wav`. This is a scalar, a 1-d, or a 2-d array depending on the dimensionality of the grid.

4.2.3 Density structures

hyperion.densities.FlaredDisk

class `hyperion.densities.`**`FlaredDisk`**(*mass=None*, *rho_0=None*, *rmin=None*, *rmax=None*, *p=-1*, *beta=-1.25*, *h_0=None*, *r_0=None*, *cylindrical_inner_rim=True*, *cylindrical_outer_rim=True*, *star=None*, *dust=None*)

This class implements the density structure for a flared axisymmatric disk, with a density given by:

$$\rho(R, z, \phi) = \rho_0^{\rm disk} \left(\frac{R_0}{R}\right)^{\beta-p} \exp\left[-\frac{1}{2}\left(\frac{z}{h(R)}\right)^2\right]$$

where

$$h(R) = h_0 \left(\frac{R}{R_0} \right)^{\beta}$$

The $\rho_0^{\rm disk}$ parameter does not need to be set directly (although it can be), and is instead automatically calculated when you set the disk mass. The exact equation relating $\rho_0^{\rm disk}$ to the disk mass can be found by integrating the equation for $\rho(R, z, \phi)$ over three dimensions and setting the result equal to the disk mass.

Once the *FlaredDisk* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.util.constants import msun, au
>>> from hyperion.densities.flared_disk import FlaredDisk
>>> disk = FlaredDisk()
>>> disk.mass = 2. * msun
>>> disk.rmin = 0.1 * au
>>> disk.rmax = 100 * au
```

Attributes

mass	Total disk mass (g)
rho_0	Scale-factor for the disk density (g/cm^3)
rmin	inner radius (cm)
rmax	outer radius (cm)
p	surface density power-law exponent
beta	scaleheight power-law exponent
h_0	scaleheight of the disk at r_0 (cm)
r_0	radius at which h_0 is defined (cm)
cylindrical_inner_rim	Whether the inner edge of the disk should be defined as a truncation
cylindrical_outer_rim	Whether the outer edge of the disk should be defined as a truncation
dust	dust properties (filename or dust object)

Methods

Methods (detail)

density(*grid*)
Return the density grid

Parameters **grid** : *SphericalPolarGrid* or *CylindricalPolarGrid* instance.

The spherical or cylindrical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the disk inside each cell. The shape of this array is the same as `grid.shape`.

midplane_cumulative_density(*r*)
Find the cumulative column density as a function of radius.

The cumulative density is measured outwards from the origin, and in the midplane.

Parameters **r** : np.ndarray

Array of values of the radius up to which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

vertical_cumulative_density(*r*, *theta*)

Find the cumulative column density as a function of theta.

Parameters **r** : float

The spherical radius at which to calculate the cumulative density.

theta : np.ndarray

The theta values at which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

hyperion.densities.AlphaDisk

class hyperion.densities.**AlphaDisk**(*mass=None*, *rho_0=None*, *rmin=None*, *rmax=None*, *p=-1*, *beta=-1.25*, *h_0=None*, *r_0=None*, *cylindrical_inner_rim=True*, *cylindrical_outer_rim=True*, *mdot=None*, *lvisc=None*, *star=None*, *dust=None*)

This class implements the density structure for an alpha-accretion disk as implemented in Whitney et al. (2003), with a density given by:

$$\rho(R, z, \phi) = \rho_0^{\rm disk} \left(1 - \sqrt{\frac{R_\star}{R}}\right) \left(\frac{R_0}{R}\right)^{\beta - p} \exp\left[-\frac{1}{2}\left(\frac{z}{h(R)}\right)^2\right]$$

where

$$h(R) = h_0 \left(\frac{R}{R_0}\right)^\beta$$

The $\rho_0^{\rm disk}$ parameter does not need to be set directly (although it can be), and is instead automatically calculated when you set the disk mass. The exact equation relating $\rho_0^{\rm disk}$ to the disk mass can be found by integrating the equation for $\rho(R, z, \phi)$ over three dimensions and setting the result equal to the disk mass.

Once the *AlphaDisk* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.util.constants import msun, au
>>> from hyperion.densities.alpha_disk import AlphaDisk
>>> disk = AlphaDisk()
>>> disk.mass = 2. * msun
>>> disk.rmin = 0.1 * au
>>> disk.rmax = 100 * au
```

The difference between *FlaredDisk* and *AlphaDisk* is that the latter includes an extra term in the density equation ($1 - \sqrt{R_0/R}$) but most importantly that it allows for viscous accretion luminosity, specified either

via an accretion rate, or an accretion luminosity. The relation between the accretion rate and the accretion luminosity in an infinitesimal volume is:

$$\frac{d\dot{E}_{\rm acc}}{dV} = \frac{3GM_\star \dot{M}_{\rm acc}}{\sqrt{32\pi^3}R^3 h(R)} \left(1 - \sqrt{\frac{R_\star}{R}}\right) \exp\left[-\frac{1}{2}\left(\frac{z}{h(R)}\right)^2\right]$$

This is equation (4) from Whitney et al. (2003). Once integrated over the whole disk, this gives a total luminosity of:

$$L_{\rm acc} = \frac{G\,M_\star\,M_{\rm acc}}{2}\left[3\left(\frac{1}{R_{\rm min}} - \frac{1}{R_{\rm max}}\right) - 2\left(\sqrt{\frac{R_\star}{R_{\rm min}^3}} - \sqrt{\frac{R_\star}{R_{\rm max}^3}}\right)\right]$$

Attributes

`mass`	Total disk mass (g)
`rho_0`	Scale-factor for the disk density (g/cm^3)
`rmin`	inner radius (cm)
`rmax`	outer radius (cm)
`p`	surface density power-law exponent
`beta`	scaleheight power-law exponent
`h_0`	scaleheight of the disk at `r_0` (cm)
`r_0`	radius at which `h_0` is defined (cm)
`cylindrical_inner_rim`	Whether the inner edge of the disk should be defined as a truncation
`cylindrical_outer_rim`	Whether the outer edge of the disk should be defined as a truncation
`mdot`	accretion rate (g/s)
`lvisc`	viscous accretion luminosity (ergs/s)
`star`	central star instance (needs `mass` and `radius` attributes)
`dust`	dust properties (filename or dust object)

Methods

Methods (detail)

`density`(*grid*)
Return the density grid

Parameters **grid** : *`SphericalPolarGrid`* or *`CylindricalPolarGrid`* instance.

The spherical or cylindrical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the disk inside each cell. The shape of this array is the same as `grid.shape`.

`midplane_cumulative_density`(*r*)
Find the cumulative column density as a function of radius.

The cumulative density is measured outwards from the origin, and in the midplane.

Parameters **r** : np.ndarray

Array of values of the radius up to which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

vertical_cumulative_density(*r*, *theta*)
Find the cumulative column density as a function of theta.

Parameters **r** : float

The spherical radius at which to calculate the cumulative density.

theta : np.ndarray

The theta values at which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

accretion_luminosity(*grid*)
Return the viscous accretion luminosity grid

Parameters **grid** : *SphericalPolarGrid* or *CylindricalPolarGrid* instance.

The spherical or cylindrical polar grid object containing information about the position of the grid cells.

Returns **lvisc** : np.ndarray

A 3-dimensional array containing the viscous accretion luminosity of the disk inside each cell. The shape of this array is the same as `grid.shape`.

hyperion.densities.PowerLawEnvelope

class hyperion.densities.**PowerLawEnvelope**
This class implements the density structure for a spherically symmetric power-law envelope, with a density given by:

$$\rho(r) = \rho_0^{\mathrm{env}} \left(\frac{r}{r_0}\right)^{\gamma}$$

Once the *PowerLawEnvelope* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.util.constants import msun, au, pc
>>> from hyperion.densities.power_law_envelope import PowerLawEnvelope
>>> envelope = PowerLawEnvelope()
>>> envelope.mass = msun
>>> envelope.rmin = 0.1 * au
>>> envelope.rmax = pc
```

PowerLawEnvelope instances can only be used with spherical polar grids at this time.

Attributes

mass	total mass (g)
rho_0	density at r_0 (g/cm^3)

Continued on next page

Table 4.18 – continued from previous page

`r_0`	radius at which `rho_0` is defined (cm)
`rmax`	outer radius (cm)
`rmin`	inner radius (cm)
`power`	density power-law exponent
`dust`	dust properties (filename or dust object)

Methods

Methods (detail)

`density`(*grid*, *ignore_cavity=False*)

Return the density grid

Parameters **grid** : *`SphericalPolarGrid`* or *`CylindricalPolarGrid`* instance.

The spherical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the envelope inside each cell. The shape of this array is the same as `grid.shape`.

`outermost_radius`(*rho*)

Find the outermost radius at which the density of the envelope has fallen to *rho*.

Parameters **rho** : float

The density for which to determine the radius

Returns **r** : float

The radius at which the density has fallen to `rho`

`midplane_cumulative_density`(*r*)

Find the cumulative column density as a function of radius.

The cumulative density is measured outwards from the origin, and in the midplane.

Parameters **r** : np.ndarray

Array of values of the radius up to which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

`add_bipolar_cavity`()

Add a bipolar cavity to the envelope.

Returns **cavity** : *`BipolarCavity`* instance

The bipolar cavity instance, which can then be used to set the parameters of the cavity.

hyperion.densities.UlrichEnvelope

class hyperion.densities.**UlrichEnvelope**(*mdot=None*, *rho_0=None*, *rmin=None*, *rmax=None*, *rc=None*, *ambient_density=0.0*, *star=None*)

This class implements the density structure for a rotationally flattened and infalling envelope, with a density given by:

$$\rho(r,\theta) = \frac{\dot{M}_{\rm env}}{4\pi\left(GM_\star R_{\rm c}^3\right)^{1/2}}\left(\frac{r}{R_{\rm c}}\right)^{-3/2}\left(1+\frac{\mu}{\mu_0}\right)^{-1/2}\left(\frac{\mu}{\mu_0}+\frac{2\mu_0^2 R_{\rm c}}{r}\right)^{-1} = \rho_0^{\rm env}\left(\frac{r}{R_{\rm c}}\right)^{-3/2}\left(1+\frac{\mu}{\mu_0}\right)^{-1/2}\left(\frac{\mu}{\mu_0}+\frac{2\mu_0^2 R_{\rm c}}{r}\right.$$

where mu_0 is given by the equation for the streamline:

$$\mu_0^3 + \mu_0\left(\frac{r}{R_{\rm c}}-1\right) - \mu\left(\frac{r}{R_{\rm c}}\right) = 0$$

Once the *UlrichEnvelope* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.util.constants import msun, au, pc
>>> from hyperion.densities.ulrich_envelope import UlrichEnvelope
>>> envelope = UlrichEnvelope()
>>> envelope.rho_0 = 1.e-19
>>> envelope.rmin = 0.1 * au
>>> envelope.rmax = pc
```

UlrichEnvelope instances can only be used with spherical polar grids at this time.

Attributes

mdot	infall rate (g/s)
rho_0	density factor (g/cm^3)
rmin	inner radius (cm)
rc	inner radius (cm)
rmax	outer radius (cm)
cavity	BipolarCavity instance
star	central star instance (needs a mass attribute)
dust	dust properties (filename or dust object)

Methods

Methods (detail)

density(*grid*, *ignore_cavity=False*)

Return the density grid

Parameters **grid** : *SphericalPolarGrid* or *CylindricalPolarGrid* instance.

The spherical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the envelope inside each cell. The shape of this array is the same as `grid.shape`.

outermost_radius(*rho*)

Find the outermost radius at which the density of the envelope has fallen to *rho* (in the midplane).

Parameters **rho** : float

The density for which to determine the radius

Returns **r** : float

The radius at which the density has fallen to `rho`

midplane_cumulative_density(*r*)

Find the cumulative column density as a function of radius.

The cumulative density is measured outwards from the origin, and in the midplane.

Parameters **r** : np.ndarray

Array of values of the radius up to which to tabulate the cumulative density.

Returns **rho** : np.ndarray

Array of values of the cumulative density.

add_bipolar_cavity()

Add a bipolar cavity to the envelope.

Returns **cavity** : *BipolarCavity* instance

The bipolar cavity instance, which can then be used to set the parameters of the cavity.

hyperion.densities.BipolarCavity

class hyperion.densities.**BipolarCavity**(*theta_0=None*, *power=None*, *r_0=None*, *rho_0=None*, *rho_exp=0.0*, *cap_to_envelope_density=False*, *dust=None*)

This class implements the density structure for a bipolar cavity in an envelope, with a density given by:

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-e}$$

inside a volume defined by two parabolic surfaces with half-opening angle `theta_0` at `r_0`.

Once the *BipolarCavity* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.densities.bipolar_cavity import BipolarCavity
>>> cavity = BipolarCavity()
>>> cavity.theta_0 = 10.
>>> cavity.power = 0.
```

In most cases however, you should not have to instantiate a BipolarCavity class directly, but instead you should use the `add_bipolar_cavity` method on the Envelope classes (see for example *UlrichEnvelope* or *PowerLawEnvelope* classes).

Attributes

r_0	radius at which theta_0 and rho_0 are defined (cm)
theta_0	Cavity half-opening angle at r_0
rho_0	density at r_0 (g/cm^3)
power	Power of the cavity shape
rho_exp	density power-law exponent
dust	dust properties (filename or dust object)

Methods

Methods (detail)

density(*grid*)
Return the density grid

Parameters **grid** : *SphericalPolarGrid* or *CylindricalPolarGrid* instance.

The spherical or cylindrical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the bipolar cavity inside each cell. The shape of this array is the same as `grid.shape`.

mask(*grid*)
Compute the shape of the bipolar cavity.

Parameters **grid** : *SphericalPolarGrid* or *CylindricalPolarGrid* instance.

The spherical or cylindrical polar grid object containing information about the position of the grid cells.

Returns **mask** : np.ndarray

A 3-dimensional booleand array indicating whether we are inside or outside the bipolar cavity (True is inside). The shape of this array is the same as `grid.shape`.

hyperion.densities.AmbientMedium

class hyperion.densities.**AmbientMedium**(*rho=None*, *rmin=None*, *rmax=None*, *subtract=[]*)
This class implements the density structure for an ambient density medium defined by a constant density, and an inner and outer radius.

Once the *AmbientMedium* class has been instantiated, the parameters for the density structure can be set via attributes:

```
>>> from hyperion.util.constants import au, pc
>>> from hyperion.densities.ambient_medium import AmbientMedium
>>> ambient = AmbientMedium()
>>> ambient.rho = 1.e-20  # cgs
>>> ambient.rmin = 0.1 * au  # cm
>>> ambient.rmax = pc  # cm
```

AmbientMedium instances can only be used with spherical polar grids at this time.

By default, the ambient medium simply adds a constant density `rho` of dust to the whole model between the inner and outer radius. However, it is possible to pass components that should be subtracted from the constant density using the `subtract=` argument. In the following example:

```
>>> e = PowerLawEnvelope()
>>> AmbientMedium(subtract=[e])
```

the ambient medium does not simply add a constant density `rho` of dust everywhere, but it adds dust such that the density never falls below `rho` between `rmin` and `rmax` - that is, it subtracts the density of component `e` from the `rho`, with a minimum of zero. In regions where the density of component of `e` is larger than `rho`, no dust is added.

Attributes

`rho`	Density of the ambient medium (g/cm^3)
`rmin`	inner radius (cm)
`rmax`	outer radius (cm)

Methods

Methods (detail)

`density`(*grid*)
Return the density grid

Parameters **grid** : *SphericalPolarGrid* instance.

The spherical polar grid object containing information about the position of the grid cells.

Returns **rho** : np.ndarray

A 3-dimensional array containing the density of the envelope inside each cell. The shape of this array is the same as `grid.shape`.

4.2.4 Sources

hyperion.sources.PointSource

class `hyperion.sources.`**`PointSource`**(*name=None*, *peeloff=True*, ***kwargs*)
A point source.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

`name`	A string identifying the source (optional)
`luminosity`	The bolometric luminosity of the source (ergs/s)
`temperature`	The temperature of the source (K)
`spectrum`	The spectrum of the source, specified either as an astropy.table.Table instance with `'nu'` and `'fnu'` columns, or
`position`	The cartesian position of the source `(x, y, z)` as a sequence of three floating-point values (cm)

hyperion.sources.SphericalSource

class `hyperion.sources.`**`SphericalSource`**(*name=None*, *peeloff=True*, ***kwargs*)

A spherical source

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

`name`	A string identifying the source (optional)
`luminosity`	The bolometric luminosity of the source (ergs/s)
`temperature`	The temperature of the source (K)
`spectrum`	The spectrum of the source, specified either as an astropy.table.Table instance with `'nu'` and `'fnu'` columns, or
`position`	The cartesian position of the source `(x, y, z)` as a sequence of three floating-point values (cm)
`radius`	The radius of the source (cm)
`limb`	Whether to include limb darkening

Methods

Methods (detail)

`add_spot`(**args*, ***kwargs*)

Add a spot to the source.

All arguments are passed to `SpotSource`, so see that class for more details

hyperion.sources.ExternalSphericalSource

class hyperion.sources.**ExternalSphericalSource**(*name=None*, *peeloff=True*, ***kwargs*)

An spherical external source.

This can be used for example to simulate the interstellar radiation field. This source is similar to *SphericalSource* but emits photons *inwards*.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

name	A string identifying the source (optional)
luminosity	The bolometric luminosity of the source (ergs/s)
temperature	The temperature of the source (K)
spectrum	The spectrum of the source, specified either as an astropy.table.Table instance with 'nu' and 'fnu' columns, or
position	The cartesian position of the source (x, y, z) as a sequence of three floating-point values (cm)
radius	The radius of the source (cm)

hyperion.sources.ExternalBoxSource

class hyperion.sources.**ExternalBoxSource**(*name=None*, *peeloff=True*, ***kwargs*)

An rectangular external source.

This can be used for example to simulate the interstellar radiation field. This source emits *inwards*.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

name	A string identifying the source (optional)
luminosity	The bolometric luminosity of the source (ergs/s)

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`temperature`	The temperature of the source (K)
`spectrum`	The spectrum of the source, specified either as an astropy.table.Table instance with `'nu'` and `'fnu'` columns, or
`bounds`	The cartesian boundaries of the rectangular box specified as `[[xmin, xmax], [ymin, ymax], [zmin,`

hyperion.sources.MapSource

class `hyperion.sources.`**`MapSource`**(*name=None*, *peeloff=True*, ***kwargs*)

A diffuse source.

This can be used for example to simulate the interstellar radiation field. This source emits *inwards*.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

`name`	A string identifying the source (optional)
`luminosity`	The bolometric luminosity of the source (ergs/s)
`temperature`	The temperature of the source (K)
`spectrum`	The spectrum of the source, specified either as an astropy.table.Table instance with `'nu'` and `'fnu'` columns, or
`map`	The relative luminosity in each cell, given as a Numpy array or an AMRGridView instance

hyperion.sources.PlaneParallelSource

class `hyperion.sources.`**`PlaneParallelSource`**(*name=None*, *peeloff=False*, ***kwargs*)

A circular plane-parallel source.

This source emits all photons in the same direction perpendicular to the plane of the source, and in one direction, like a beam.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

name	A string identifying the source (optional)
luminosity	The bolometric luminosity of the source (ergs/s)
temperature	The temperature of the source (K)
spectrum	The spectrum of the source, specified either as an astropy.table.Table instance with 'nu' and 'fnu' columns, or
position	The cartesian position of the source (x, y, z) as a sequence of three floating-point values (cm)
radius	The radius of the source (cm)
direction	The direction the photons should be emitted in (theta, phi) where theta and phi are spherical polar angle

hyperion.sources.PointSourceCollection

class hyperion.sources.**PointSourceCollection**(*name=None*, *peeloff=True*, ***kwargs*)

A point source.

Parameters **name** : str, optional

The name of the source

peeloff : bool, optional

Whether to peel-off photons from this source

Notes

Any additional arguments are are used to initialize attributes.

Attributes

name	A string identifying the source (optional)
luminosity	The bolometric luminosity for the N sources as a 1-D Numpy array (ergs/s)
temperature	The temperature of the source (K)
spectrum	The spectrum of the source, specified either as an astropy.table.Table instance with 'nu' and 'fnu' columns, or
position	The cartesian position of the N sources (x, y, z) as a 2-D Numpy array with shape Nx3 (cm)

4.2.5 Grid

hyperion.grid.CartesianGrid

class hyperion.grid.**CartesianGrid**(**args*)

A cartesian grid.

The grid can be initialized by passing the x, y, and z coordinates of cell walls:

```
>>> grid = CartesianGrid(x_wall, y_wall, z_wall)
```

where x_wall, y_wall, and z_wall are 1-d sequences of wall positions. The number of cells in the resulting grid will be one less in each dimension that the length of these arrays.

CartesianGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer a *CartesianGrid* object, but a *CartesianGridView* object. When setting this for the first time, this can be set either to another *CartesianGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

CartesianGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also a *CartesianGridView* object. The data can then be accessed with the `array` attribute:

```
>>> grid['density'][0].array
```

which is a 3-d array of the requested quantity.

Methods

Methods (detail)

set_walls(*x_wall*, *y_wall*, *z_wall*)

read(*group*, *quantities='all'*)
Read the geometry and physical quantities from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)
Read in geometry information from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid geometry from.

read_quantities(*group*, *quantities='all'*)
Read in physical quantities from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)
Write out the cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *array*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)

Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

array : np.ndarray

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

to_yt(*dust_id=0*)

Convert cartesian grid to a yt object (requires yt)

This can only be used for regular cartesian grids

Parameters **dust_id** : int, optional

The ID of the dust population to extract. If not set, this defaults to 0 (the first dust population).

class hyperion.grid.**CartesianGridView**(*grid*, *quantity*)

Methods

Methods (detail)

append(*grid*)
Used to append quantities from another grid

Parameters **grid** : 3D Numpy array or CartesianGridView instance

The grid to copy the quantity from

add(*grid*)
Used to add quantities from another grid

Parameters **grid** : 3D Numpy array or CartesianGridView instance

The grid to copy the quantity from

hyperion.grid.CylindricalPolarGrid

class hyperion.grid.**CylindricalPolarGrid**(**args*)
A cylindrical polar grid.

The grid can be initialized by passing the w, z, and phi coordinates of cell walls:

```
>>> grid = CylindricalPolarGrid(w_wall, z_wall, p_wall)
```

where `w_wall`, `z_wall`, and `p_wall` are 1-d sequences of wall positions. The number of cells in the resulting grid will be one less in each dimension that the length of these arrays.

CylindricalPolarGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer a *CylindricalPolarGrid* object, but a *CylindricalPolarGridView* object. When setting this for the first time, this can be set either to another *CylindricalPolarGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

CylindricalPolarGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also a *CylindricalPolarGridView* object. The data can then be accessed with the `array` attribute:

```
>>> grid['density'][0].array
```

which is a 3-d array of the requested quantity.

Methods

Methods (detail)

set_walls(*w_wall*, *z_wall*, *p_wall*)

read(*group*, *quantities='all'*)
Read the geometry and physical quantities from a cylindrical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)
Read in geometry information from a cylindrical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid geometry from.

read_quantities(*group*, *quantities='all'*)
Read in physical quantities from a cylindrical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)
Write out the cylindrical polar grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *array*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)

Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

array : np.ndarray

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

class hyperion.grid.**CylindricalPolarGridView**(*grid*, *quantity*)

Methods

Methods (detail)

append(*grid*)

Used to append quantities from another grid

Parameters **grid** : 3D Numpy array or CylindricalPolarGridView instance

The grid to copy the quantity from

add(*grid*)

Used to add quantities from another grid

Parameters **grid** : 3D Numpy array or CylindricalPolarGridView instance

The grid to copy the quantity from

hyperion.grid.SphericalPolarGrid

class hyperion.grid.**SphericalPolarGrid**(**args*)

A spherical polar grid.

The grid can be initialized by passing the r, theta, and phi coordinates of cell walls:

```
>>> grid = SphericalPolarGrid(r_wall, t_wall, p_wall)
```

where `r_wall`, `t_wall`, and `p_wall` are 1-d sequences of wall positions. The number of cells in the resulting grid will be one less in each dimension that the length of these arrays.

SphericalPolarGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer a *SphericalPolarGrid* object, but a *SphericalPolarGridView* object. When setting this for the first time, this can be set either to another *SphericalPolarGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

SphericalPolarGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also a *SphericalPolarGridView* object. The data can then be accessed with the `array` attribute:

```
>>> grid['density'][0].array
```

which is a 3-d array of the requested quantity.

Methods

Methods (detail)

set_walls(*r_wall*, *t_wall*, *p_wall*)

read(*group*, *quantities='all'*)

Read the geometry and physical quantities from a spherical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)

Read in geometry information from a spherical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid geometry from.

read_quantities(*group*, *quantities='all'*)

Read in physical quantities from a spherical polar grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)

Write out the spherical polar grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *array*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)

Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

array : np.ndarray

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

class hyperion.grid.**SphericalPolarGridView**(*grid*, *quantity*)

Methods

Methods (detail)

append(*grid*)

Used to append quantities from another grid

Parameters **grid** : 3D Numpy array or SphericalPolarGridView instance

The grid to copy the quantity from

add(*grid*)

Used to add quantities from another grid

Parameters **grid** : 3D Numpy array or SphericalPolarGridView instance

The grid to copy the quantity from

hyperion.grid.AMRGrid

class hyperion.grid.**AMRGrid**(*amr_grid=None*)

An AMR grid.

Levels are stored in the `levels` attribute, which is a list of `hyperion.grid.amr_grid.Level` objects, which in turn contain a `grids` attribute which is a list of `Grid` objects.

Levels can be added with:

```
level = amr.add_level()
```

And grids can be added to a level with:

```
grid = level.add_grid()
```

Grid objects have the following attributes which should be set:

- `xmin` - lower x position of the grid
- `xmax` - upper x position of the grid
- `ymin` - lower y position of the grid
- `ymax` - upper y position of the grid

- `zmin` - lower z position of the grid
- `zmax` - upper z position of the grid
- `nx` - number of cells in x direction
- `ny` - number of cells in y direction
- `nz` - number of cells in z direction
- `quantities` - a dictionary containing physical quantities (see below)

AMRGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer an *AMRGrid* object, but a *AMRGridView* object. When setting this for the first time, this can be set either to another *AMRGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

AMRGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also an *AMRGridView* object.

Methods

Methods (detail)

read(*group*, *quantities='all'*)
Read the geometry and physical quantities from an AMR grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)
Read in geometry information from an AMR grid

Parameters **group** : h5py.Group

The HDF5 group to read the geometry from

read_quantities(*group*, *quantities='all'*)
Read in physical quantities from an AMR grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)

Write out the AMR grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *amr_grid*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)

Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

amr_grid : AMRGridView

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

to_yt(*dust_id=0*)
Convert AMR grid to a yt object (requires yt)

Parameters **dust_id** : int, optional

The ID of the dust population to extract. If not set, this defaults to 0 (the first dust population).

classmethod from_yt(*ds*, *quantity_mapping={}*)
Convert a yt dataset to a Hyperion AMRGrid object

Note: This method requires yt 3.0 or later

Parameters **ds** : yt Dataset

The yt dataset

quantity_mapping : dict

A dictionary mapping the name of the quantity to use in Hyperion (the key) to the name of the field to extract in yt (the value).

Notes

The domain is always re-centered so that the position at ds.domain_center in yt becomes the origin in Hyperion.

Examples

Assuming that your dust opacities are defined per unit gas mass, and the simulation density is given in gas densities, converting is straightfoward (in this case we assume the density field is called `('gas', 'density')`):

```
>>> from yt import load
>>> from hyperion.grid import AMRGrid
>>> ds = load('DD0010/moving7_0010')
>>> amr = AMRGrid.from_yt(ds, quantity_mapping={'density':('gas', 'density')})
```

However, you will need to take care if your dust opacities are defined in dust mass units. If the yt dataset does not contain dust densities, you can add a field yourself, for example:

```
>>> from yt import load
>>> from hyperion.grid import AMRGrid
>>> ds = load('DD0010/moving7_0010')
>>> def _dust_density(field, data):
...     return data[('gas', 'density')].in_units('g/cm**3') * 0.01
>>> ds.add_field(('gas', 'dust_density'), function=_dust_density, units='g/cm**3')

>>> amr = AMRGrid.from_yt(ds, quantity_mapping={'density':('gas', 'dust_density')})
```

class hyperion.grid.**AMRGridView**(*amr_grid*, *quantity*)

Methods

Methods (detail)

append(*amr_grid_view*)
Used to append quantities from another grid

Parameters **amr_grid** : AMRGridView instance

The grid to copy the quantity from

add(*amr_grid_view*)
Used to add quantities from another grid

Parameters **amr_grid** : AMRGridView instance

The grid to copy the quantity from

hyperion.grid.OctreeGrid

class hyperion.grid.**OctreeGrid**(**args*)
An octree grid.

To initialize an Octree object, use:

```
>>> grid = OctreeGrid(x, y, z, dx, dy, dz, refined)
```

where `x`, `y`, and `z` are the cartesian coordinates of the center of the grid, `dx`, `dy`, and `dz` are the half-widths of the grid, and `refined` is a sequence of boolean values that indicate whether a given cell is refined.

The first value of the `refined` sequence indicates whether the parent cell is sub-divided. If it is, then the the second element indicates whether the first cell of the parent cell is sub-divided. If it isn't, then the next value indicates whether the second cell of the parent cell is sub-divided. If it is, then we need to specify the booleans for all the children of that cell before we move to the third cell of the parent cell.

For example, the simplest grid is a single cell that is not sub-divided:

```
refined = [False]
```

The next simplest grid is a single grid cell that is only sub-divided once:

```
refined = [True, False, False, False, False, False, False, False, False]
```

It is easier to picture this as a hierarchy:

```
refined = [True,
               False,
               False,
               False,
               False,
               False,
               False,
               False,
               False,
               ]
```

If we sub-divide the third sub-cell in the parent cell into cells that are themselves not sub-divided, we get:

```
refined = [True,
           False,
           False,
           True,
             False,
             False,
             False,
             False,
             False,
             False,
             False,
             False,
           False,
           False,
           False,
           False,
           False,
           ]
```

and so on. The order of the sub-cells is first along x, then along y, then along z.

OctreeGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer an *OctreeGrid* object, but a *OctreeGridView* object. When setting this for the first time, this can be set either to another *OctreeGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

OctreeGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also an *OctreeGridView* object.

Methods

Methods (detail)

set_walls(*x*, *y*, *z*, *dx*, *dy*, *dz*, *refined*)

read(*group*, *quantities='all'*)

Read the geometry and physical quantities from an octree grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)
Read in geometry information from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid geometry from.

read_quantities(*group*, *quantities='all'*)
Read in physical quantities from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)
Write out the octree grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions (ignored for this kind of grid)

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *array*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)
Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

array : np.ndarray

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

to_yt(*dust_id=0*)
Convert AMR grid to a yt object (requires yt)

Parameters **dust_id** : int, optional

The ID of the dust population to extract. If not set, this defaults to 0 (the first dust population).

class hyperion.grid.**OctreeGridView**(*grid*, *quantity*)

Methods

Methods (detail)

append(*grid*)
Used to append quantities from another grid

Parameters **grid** : 1D Numpy array or OctreeGridView instance

The grid to copy the quantity from

add(*grid*)
Used to add quantities from another grid

Parameters **grid** : 1D Numpy array or OctreeGridView instance

The grid to copy the quantity from

hyperion.grid.VoronoiGrid

class hyperion.grid.**VoronoiGrid**(**args*, ***kwargs*)
A voronoi mesh.

The mesh can be initialized by passing the x, y, and z coordinates of the points used to compute the mesh:

```
>>> grid = Voronoi(x, y, z)
```

where `x`, `y`, and `z` are 1-d sequences of point positions.

VoronoiGrid objects may contain multiple quantities (e.g. density, specific energy). To access these, you can specify the name of the quantity as an item:

```
>>> grid['density']
```

which is no longer a *VoronoiGrid* object, but a *VoronoiGridView* object. When setting this for the first time, this can be set either to another *VoronoiGridView* object, an external h5py link, or an empty list. For example, the following should work:

```
>>> grid['density_new'] = grid['density']
```

VoronoiGridView objects allow the specific dust population to be selected as an index:

```
>>> grid['density'][0]
```

Which is also a *VoronoiGridView* object. The data can then be accessed with the `array` attribute:

```
>>> grid['density'][0].array
```

which is a 1-d array of the requested quantity.

Methods

Methods (detail)

read(*group*, *quantities='all'*)
Read the geometry and physical quantities from an voronoi grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid from. This group should contain groups named 'Geometry' and 'Quantities'.

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

read_geometry(*group*)
Read in geometry information from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid geometry from.

read_quantities(*group*, *quantities='all'*)
Read in physical quantities from a cartesian grid

Parameters **group** : h5py.Group

The HDF5 group to read the grid quantities from

quantities : 'all' or list

Which physical quantities to read in. Use 'all' to read in all quantities or a list of strings to read only specific quantities.

write(*group*, *quantities='all'*, *copy=True*, *absolute_paths=False*, *compression=True*, *wall_dtype=<type 'float'>*, *physics_dtype=<type 'float'>*)
Write out the voronoi grid

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

quantities : 'all' or list

Which physical quantities to write out. Use 'all' to write out all quantities or a list of strings to write only specific quantities.

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions (ignored for this kind of grid)

physics_dtype : type

The datatype to use to write the physical quantities

write_single_array(*group*, *name*, *array*, *copy=True*, *absolute_paths=False*, *compression=True*, *physics_dtype=<type 'float'>*)

Write out a single quantity, checking for consistency with geometry

Parameters **group** : h5py.Group

The HDF5 group to write the grid to

name : str

The name of the array in the group

array : np.ndarray

The array to write out

copy : bool

Whether to copy external links, or leave them as links.

absolute_paths : bool

If copy is False, then this indicates whether to use absolute or relative paths for links.

compression : bool

Whether to compress the arrays in the HDF5 file

wall_dtype : type

The datatype to use to write the wall positions

physics_dtype : type

The datatype to use to write the physical quantities

add_derived_quantity(*name*, *function*)

evaluate_function_average(*func*, *n_samples=None*, *min_cell_samples=None*)
Evaluate the average of a function inside each cell using randomly sampled points inside each cell.

Note: This feature is still experimental, use with caution

Parameters **func** : function

The function to evaluate in each cell. This should take three 1-d arrays of `x`, `y`, and `z` and return a 1-d array of values.

n_samples : int

The total number of points to sample within the domain. Points will be uniformly sampled in each Voronoi cell so that at least `n_samples` total points will be produced. Each cell will contain a number of samples proportional to its volume (but at least `min_cell_samples` points will always be sampled in each cell).

min_cell_samples : int

The minimum number of samples per cell.

class hyperion.grid.**VoronoiGridView**(*grid*, *quantity*)

Methods

Methods (detail)

append(*grid*)
Used to append quantities from another grid

Parameters **grid** : 1D Numpy array or VoronoiGridView instance

The grid to copy the quantity from

add(*grid*)
Used to add quantities from another grid

Parameters **grid** : 1D Numpy array or VoronoiGridView instance

The grid to copy the quantity from

Images and SED configuration

hyperion.conf.PeeledImageConf

class hyperion.conf.**PeeledImageConf**(***kwargs*)

Method

Methods (detail)

set_aperture_radii(*n_ap*, *ap_min*, *ap_max*)
Set the range of apertures to use for SEDs/Images

Parameters **n_ap** : int

The number of apertures to compute SEDs in

ap_min, ap_max : float

The smallest and largest aperture to use, in cm

set_depth(*d_min*, *d_max*)
Set the minimum and maximum distance between which photons should be peeled off.

By default, d_min and d_max are set to -inf and +inf respectively. This option can be useful to compute for example models in a spherical polar grid, but including only the photons in a slab.

Parameters **d_min, d_max** : float

The minimum and maximum distance between which photons should be peeled-off. Distance increases away from the observer, and d_min and d_max are the distances closest and furthest from the observer respectively. The origin is the position of the observer if inside the model, otherwise it is the origin of the grid.

set_ignore_optical_depth(*ignore_optical_depth*)
Ingore optical depth when creating images.

This is useful in cases where one wants to understand how much the optical depth is affecting a set of images.

Parameters **ignore_optical_depth** : bool

Whether to ignore optical depth effects (default is False)

set_image_limits(*xmin*, *xmax*, *ymin*, *ymax*)
Set the extent of the output images

Parameters **xmin, xmax, ymin, ymax** : float

The extent of the images, which are either in cm (if using standard binned images or peeloff images) or in degrees (if using peeling off to a point inside the model).

set_image_size(*n_x*, *n_y*)
Set the size of the output images

Parameters **n_x, n_y** : int

The number of pixels in the x and y directions

set_inside_observer(*position*)
Set the observer to be inside the model

Parameters **position** : tuple of 3 floats

The spatial coordinates of the observer, in cm

set_output_bytes(*io_bytes*)
Set whether to output images/SEDs in 32-bit or 64-bit.

Parameters **io_bytes** : int

The number of bytes for the output. This should be either 4 (for 32-bit) or 8 (for 64-bit).

set_peeloff_origin(*position*)
Set the origin for the peeloff.

Parameters **position** : tuple of 3 floats

The coordinates of the origin of the peeling-off, in cm

set_stokes(*stokes*)
Set whether to save the full Stokes vector for the images/SEDs.

If set to *False*, only the I component is saved.

Parameters **stokes** : bool

Whether to save the full Stokes vector for the images/SEDs.

set_track_origin(*track_origin*, *n_scat=None*)
Set whether to track the origin of the photons. The options are:

'no' - does not split up the images/SEDs by origin

'basic' - this splits up the images/SEDs into:

- The photons last emitted from a source and did not undergo any subsequent interactions.
- The photons last emitted from dust and did not undergo any subsequent interactions
- The photons last emitted from a source and subsequently scattered
- The photons last emitted from dust and subsequently scattered

'detailed' - as above, but in each category, the origin is further refined into each individual source and dust type.

'scatterings' - as for 'basic', but splitting the scatterings into the images for 1, 2, 3, ..., `n_scat` scatterings since the last emission.

Parameters **track_origin** : bool

Whether to track the origin of the photons as described above.

set_uncertainties(*uncertainties*)
Set whether to compute uncertainties on the images/SEDs

Parameters **uncertainties** : bool

Whether to compute uncertainties on the images/SEDs.

set_viewing_angles(*theta*, *phi*)
Set the viewing angles to use

Parameters **theta, phi** : iterable of floats

The viewing angles to compute SEDs for.

Examples

Set viewing angles using lists of well-defined angles:

```
>>> image.set_viewing_angles([30.,55.,87.],[22.,44.,34.])
```

Set viewing angles using generated numpy arrays:

```
>>> image.set_viewing_angles(np.linspace(0.,90.,10), np.repeat(30.,10))
```

Set a single viewing direction:

```
>>> image.set_viewing_angles([77.],[25.])
```

set_wavelength_index_range (*iwav_min*, *iwav_max*)
Set the range of wavelengths to use for SEDs/Images

This is intended to be used when the monochromatic option is turned on.

Parameters **iwav_min, iwav_max** : int

The index of the first and last frequency to compute SEDs/Images for. This is the index in the array of wavelengths used when calling `set_monochromatic`.

set_wavelength_range (*n_wav*, *wav_min*, *wav_max*)
Set the range of wavelengths to use for SEDs/Images

Parameters **n_wav** : int

The number of wavelengths to compute SEDs/Images for

wav_min, wav_max : float

The smallest and largest wavelength to use, in microns

hyperion.conf.BinnedImageConf

class `hyperion.conf.`**BinnedImageConf** (*n_theta=None*, *n_phi=None*, ***kwargs*)

Method

Methods (detail)

set_aperture_radii (*n_ap*, *ap_min*, *ap_max*)
Set the range of apertures to use for SEDs/Images

Parameters **n_ap** : int

The number of apertures to compute SEDs in

ap_min, ap_max : float

The smallest and largest aperture to use, in cm

set_image_limits (*xmin*, *xmax*, *ymin*, *ymax*)
Set the extent of the output images

Parameters **xmin, xmax, ymin, ymax** : float

The extent of the images, which are either in cm (if using standard binned images or peeloff images) or in degrees (if using peeling off to a point inside the model).

set_image_size (*n_x*, *n_y*)
Set the size of the output images

Parameters **n_x, n_y** : int

The number of pixels in the x and y directions

set_output_bytes(*io_bytes*)
Set whether to output images/SEDs in 32-bit or 64-bit.

Parameters io_bytes : int

The number of bytes for the output. This should be either 4 (for 32-bit) or 8 (for 64-bit).

set_stokes(*stokes*)
Set whether to save the full Stokes vector for the images/SEDs.

If set to *False*, only the I component is saved.

Parameters stokes : bool

Whether to save the full Stokes vector for the images/SEDs.

set_track_origin(*track_origin*, *n_scat=None*)
Set whether to track the origin of the photons. The options are:

'no' - does not split up the images/SEDs by origin

'basic' - this splits up the images/SEDs into:

- The photons last emitted from a source and did not undergo any subsequent interactions.
- The photons last emitted from dust and did not undergo any subsequent interactions
- The photons last emitted from a source and subsequently scattered
- The photons last emitted from dust and subsequently scattered

'detailed' - as above, but in each category, the origin is further refined into each individual source and dust type.

'scatterings' - as for 'basic', but splitting the scatterings into the images for 1, 2, 3, ..., `n_scat` scatterings since the last emission.

Parameters track_origin : bool

Whether to track the origin of the photons as described above.

set_uncertainties(*uncertainties*)
Set whether to compute uncertainties on the images/SEDs

Parameters uncertainties : bool

Whether to compute uncertainties on the images/SEDs.

set_viewing_bins(*n_theta*, *n_phi*)
Set the number of viewing angles to use

Parameters n_theta, n_phi :

The number of viewing angles to use in the theta and phi directions respectively.

set_wavelength_index_range(*iwav_min*, *iwav_max*)
Set the range of wavelengths to use for SEDs/Images

This is intended to be used when the monochromatic option is turned on.

Parameters iwav_min, iwav_max : int

The index of the first and last frequency to compute SEDs/Images for. This is the index in the array of wavelengths used when calling `set_monochromatic`.

set_wavelength_range(*n_wav*, *wav_min*, *wav_max*)
Set the range of wavelengths to use for SEDs/Images

Parameters **n_wav** : int

The number of wavelengths to compute SEDs/Images for

wav_min, wav_max : float

The smallest and largest wavelength to use, in microns

4.2.6 Outputs

hyperion.model.SED

class hyperion.model.**SED**(*nu*, *val=None*, *unc=None*, *units=None*)
Class to represent an SED or set of SEDs

Parameters **nu** : ndarray

The frequencies at which the SED is defined, in Hz

val : ndarray, optional

The values for the SED. The last dimensions should match the number of frequencies.

unc : ndarray, optional

The uncertainties for the SED values. The last dimensions should match the number of frequencies.

units : str

The units of the values

Attributes

wav	The wavelengths for which the SED is defined (in microns).
nu	The frequencies for which the SED is defined (in Hz)
val	The SED values (fluxes, flux densities, surface brightness, or polarization) in the units given by the .unit p
unc	The uncertainties on the SED values in the units given by the .unit property.
unit	The units of the SED values.
ap_min	Minimum aperture used to define the SEDs (in cm).
ap_max	Maximum aperture used to define the SEDs (in cm).
distance	Distance assumed for the image (in cm).
inside_observer	Whether the image was from an inside observer.

hyperion.model.Image

class hyperion.model.**Image**(*nu*, *val=None*, *unc=None*, *units=None*)
Class to represent an image or set of images

Parameters **nu** : ndarray

The frequencies at which the image is defined, in Hz

val : ndarray, optional

The values for the image. The last dimensions should match the number of frequencies.

unc : ndarray, optional

The uncertainties for the image values. The last dimensions should match the number of frequencies.

units : str

The units of the values

Attributes

`wav`	The wavelengths for which the image is defined (in microns).
`nu`	The frequencies for which the image is defined (in Hz).
`val`	The image values (fluxes, flux densities, surface brightness, or polarization) in the units given by the `.unit`
`unc`	The uncertainties on the image values in the units given by the `.unit` property.
`unit`	The units of the image values.
`x_min`	Lower extent of the image in the x direction (in cm).
`x_max`	Upper extent of the image in the x direction (in cm).
`y_min`	Lower extent of the image in the y direction (in cm).
`y_max`	Upper extent of the image in the y direction (in cm).
`lon_min`	Lower extent of the image in the x direction (in degrees).
`lon_max`	Upper extent of the image in the x direction (in degrees).
`lat_min`	Lower extent of the image in the y direction (in degrees).
`lat_max`	Upper extent of the image in the y direction (in degrees).
`distance`	Distance assumed for the image (in cm).
`pix_area_sr`	Pixel area (in steradians).
`inside_observer`	Whether the image was from an inside observer.

4.2.7 Dust

hyperion.dust.SphericalDust

class `hyperion.dust.`**`SphericalDust`**(**args*)

This class should be used in cases where fully arbitrary dust properties need to be specified, within the framework of randomly oriented grains, which means that the scattering phase function has the general form:

$$R(\theta) = \begin{bmatrix} P_1 & P_2 & 0 & 0 \\ P_2 & P_1 & 0 & 0 \\ 0 & 0 & P_3 & -P_4 \\ 0 & 0 & P_4 & P_3 \end{bmatrix}$$

This class is initialized with:

```
d = SphericalDust()
```

and the properties should then be set manually. See here for a description of the available properties and how to set them.

Method

Methods (detail)

set_sublimation_temperature(*mode*, *temperature=0.0*)
Set the dust sublimation mode and temperature.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation temperature
- **'slow' - reduce the dust in cells exceeding the** sublimation temperature
- **'cap' - any temperature exceeding the sublimation** temperature is reset to the sublimation temperature.

temperature : float, optional

The dust sublimation temperature, in K

set_sublimation_specific_energy(*mode*, *specific_energy=0.0*)
Set the dust sublimation mode and specific energy.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation specific energy
- **'slow' - reduce the dust in cells exceeding the** sublimation specific energy
- **'cap' - any specific energy exceeding the sublimation** specific energy is reset to the sublimation specific energy.

specific_energy : float, optional

The dust sublimation specific energy, in cgs

set_lte_emissivities(*n_temp=1200*, *temp_min=0.1*, *temp_max=100000.0*)
Calculate the emissivities assuming LTE

Parameters **n_temp** : int, optional

The number of temperatures to calculate the emissivities for

temp_min : float, optional

The minimum temperature to calculate the emissivities for

temp_max : float, optional

The maximum temperature to calculate the emissivities for

plot(*filename*)

read(*filename*)
Read in from a standard dust file

write(*filename*, *compression=True*)
Write out to a standard dust file, including calculations of the mean opacities and optionally thermal emissivities.

temperature2specific_energy(*temperature*)
Convert a temperature to its corresponding specific energy value.

Parameters **temperature** : float or array_like

The temperature to convert

Returns **specific_energy** : float or array_like

The specific energy corresponding to the input temperature

specific_energy2temperature(*specific_energy*)
Convert a specific energy value to its corresponding temperature.

Parameters **specific_energy** : float or array_like

The specific energy to convert

Returns **temperature** : float or array_like

The temperature corresponding to the input specific energy

chi_nu_temperature(*temperature*)
Compute the mean opacity to extinction for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_temperature(*temperature*)
Compute the mean opacity to absorption for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **kappa_nu_mean** : float

The mean opacity to absorption

chi_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to extinction for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to absorption for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **kappa_nu_mean** : float

The mean opacity to absorption

hyperion.dust.IsotropicDust

class `hyperion.dust.`**`IsotropicDust`**(*nu*, *albedo*, *chi*)

This class should be used for dust properties that include isotropic scattering. The dust properties should be instatiated as:

```
d = IsotropicDust(nu, albedo, chi)
```

where `nu`, `albedo`, and `chi` are 1-D Numpy arrays containing the frequencies, albedo, and opacity to extinction respectively.

Method

Methods (detail)

`set_sublimation_temperature`(*mode*, *temperature=0.0*)

Set the dust sublimation mode and temperature.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation temperature
- **'slow' - reduce the dust in cells exceeding the** sublimation temperature
- **'cap' - any temperature exceeding the sublimation** temperature is reset to the sublimation temperature.

temperature : float, optional

The dust sublimation temperature, in K

`set_sublimation_specific_energy`(*mode*, *specific_energy=0.0*)

Set the dust sublimation mode and specific energy.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation

- **'fast' - remove all dust in cells exceeding the** sublimation specific energy
- **'slow' - reduce the dust in cells exceeding the** sublimation specific energy
- **'cap' - any specific energy exceeding the sublimation** specific energy is reset to the sublimation specific energy.

specific_energy : float, optional

The dust sublimation specific energy, in cgs

set_lte_emissivities(*n_temp=1200*, *temp_min=0.1*, *temp_max=100000.0*)
Calculate the emissivities assuming LTE

Parameters **n_temp** : int, optional

The number of temperatures to calculate the emissivities for

temp_min : float, optional

The minimum temperature to calculate the emissivities for

temp_max : float, optional

The maximum temperature to calculate the emissivities for

plot(*filename*)

read(*filename*)
Read in from a standard dust file

write(*filename*, *compression=True*)
Write out to a standard dust file, including calculations of the mean opacities and optionally thermal emissivities.

temperature2specific_energy(*temperature*)
Convert a temperature to its corresponding specific energy value.

Parameters **temperature** : float or array_like

The temperature to convert

Returns **specific_energy** : float or array_like

The specific energy corresponding to the input temperature

specific_energy2temperature(*specific_energy*)
Convert a specific energy value to its corresponding temperature.

Parameters **specific_energy** : float or array_like

The specific energy to convert

Returns **temperature** : float or array_like

The temperature corresponding to the input specific energy

chi_nu_temperature(*temperature*)
Compute the mean opacity to extinction for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_temperature(*temperature*)

Compute the mean opacity to absorption for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **kappa_nu_mean** : float

The mean opacity to absorption

chi_nu_spectrum(*nu*, *fnu*)

Compute the mean opacity to extinction for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_spectrum(*nu*, *fnu*)

Compute the mean opacity to absorption for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **kappa_nu_mean** : float

The mean opacity to absorption

hyperion.dust.HenyeyGreensteinDust

class hyperion.dust.**HenyeyGreensteinDust**(*nu*, *albedo*, *chi*, *g*, *p_lin_max*)

This class should be used for dust properties that include scattering parameterized by the Henyey-Greenstein, 1941 function. The dust properties should be instatiated as:

```
d = HenyeyGreensteinDust(nu, albedo, chi, g, p_lin_max)
```

where `nu`, `albedo`, and `chi` are 1-D Numpy arrays containing the frequencies, albedo, and opacity to extinction respectively, and `g` and `p_lin_max` are also 1-D Numpy arrays containing the asymmetry parameter and the maximum linear polarization.

Method

Methods (detail)

set_sublimation_temperature(*mode*, *temperature=0.0*)
Set the dust sublimation mode and temperature.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation temperature
- **'slow' - reduce the dust in cells exceeding the** sublimation temperature
- **'cap' - any temperature exceeding the sublimation** temperature is reset to the sublimation temperature.

temperature : float, optional

The dust sublimation temperature, in K

set_sublimation_specific_energy(*mode*, *specific_energy=0.0*)
Set the dust sublimation mode and specific energy.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation specific energy
- **'slow' - reduce the dust in cells exceeding the** sublimation specific energy
- **'cap' - any specific energy exceeding the sublimation** specific energy is reset to the sublimation specific energy.

specific_energy : float, optional

The dust sublimation specific energy, in cgs

set_lte_emissivities(*n_temp=1200*, *temp_min=0.1*, *temp_max=100000.0*)
Calculate the emissivities assuming LTE

Parameters **n_temp** : int, optional

The number of temperatures to calculate the emissivities for

temp_min : float, optional

The minimum temperature to calculate the emissivities for

temp_max : float, optional

The maximum temperature to calculate the emissivities for

plot(*filename*)

read(*filename*)
Read in from a standard dust file

write(*filename*, *compression=True*)
Write out to a standard dust file, including calculations of the mean opacities and optionally thermal emissivities.

temperature2specific_energy(*temperature*)
Convert a temperature to its corresponding specific energy value.

Parameters **temperature** : float or array_like

The temperature to convert

Returns **specific_energy** : float or array_like

The specific energy corresponding to the input temperature

specific_energy2temperature(*specific_energy*)
Convert a specific energy value to its corresponding temperature.

Parameters **specific_energy** : float or array_like

The specific energy to convert

Returns **temperature** : float or array_like

The temperature corresponding to the input specific energy

chi_nu_temperature(*temperature*)
Compute the mean opacity to extinction for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_temperature(*temperature*)
Compute the mean opacity to absorption for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **kappa_nu_mean** : float

The mean opacity to absorption

chi_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to extinction for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to absorption for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **kappa_nu_mean** : float

The mean opacity to absorption

hyperion.dust.HOCHUNKDust

class `hyperion.dust.`**`HOCHUNKDust`**(*filename*)

This class should be used for dust properties that include scattering parameterized by the Henyey-Greenstein, 1941 function, which are formatted for the HOCHUNK code. The dust properties should be instatiated as:

```
d = HOCHUNKDust(filename)
```

where `filename` is the name of the file containing the dust properties in the HOCHUNK format.

Method

Methods (detail)

`set_sublimation_temperature`(*mode*, *temperature=0.0*)

Set the dust sublimation mode and temperature.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation temperature
- **'slow' - reduce the dust in cells exceeding the** sublimation temperature
- **'cap' - any temperature exceeding the sublimation** temperature is reset to the sublimation temperature.

temperature : float, optional

The dust sublimation temperature, in K

`set_sublimation_specific_energy`(*mode*, *specific_energy=0.0*)

Set the dust sublimation mode and specific energy.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation specific energy

- **'slow' - reduce the dust in cells exceeding the** sublimation specific energy
- **'cap' - any specific energy exceeding the sublimation** specific energy is reset to the sublimation specific energy.

specific_energy : float, optional

The dust sublimation specific energy, in cgs

set_lte_emissivities(*n_temp=1200*, *temp_min=0.1*, *temp_max=100000.0*)
Calculate the emissivities assuming LTE

Parameters **n_temp** : int, optional

The number of temperatures to calculate the emissivities for

temp_min : float, optional

The minimum temperature to calculate the emissivities for

temp_max : float, optional

The maximum temperature to calculate the emissivities for

plot(*filename*)

read(*filename*)
Read in from a standard dust file

write(*filename*, *compression=True*)
Write out to a standard dust file, including calculations of the mean opacities and optionally thermal emissivities.

temperature2specific_energy(*temperature*)
Convert a temperature to its corresponding specific energy value.

Parameters **temperature** : float or array_like

The temperature to convert

Returns **specific_energy** : float or array_like

The specific energy corresponding to the input temperature

specific_energy2temperature(*specific_energy*)
Convert a specific energy value to its corresponding temperature.

Parameters **specific_energy** : float or array_like

The specific energy to convert

Returns **temperature** : float or array_like

The temperature corresponding to the input specific energy

chi_nu_temperature(*temperature*)
Compute the mean opacity to extinction for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_temperature(*temperature*)
Compute the mean opacity to absorption for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **kappa_nu_mean** : float

The mean opacity to absorption

chi_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to extinction for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to absorption for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **kappa_nu_mean** : float

The mean opacity to absorption

hyperion.dust.BHDust

class hyperion.dust.**BHDust**(*model*)
This class should be used for dust properties that were computed using this dust calculation code which is a wrapper to the bhmie routine originally written by C.F. Bohren and D. Huffman and improved by B. Draine.

When using the bhmie code, you should set the output format to 2, which will create a number of files ending in .wav, .mu, .alb, etc. Then, instantiate this class with the name of the directory containing these output files along with the prefix used. For example, if you use directory/mydust as a prefix in bhmie, you can import this dust with:

```
>>> from hyperion.dust import BHDust
>>> d = BHDust('directory/mydust')
```

Method

Methods (detail)

set_sublimation_temperature(*mode*, *temperature=0.0*)
Set the dust sublimation mode and temperature.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation temperature
- **'slow' - reduce the dust in cells exceeding the** sublimation temperature
- **'cap' - any temperature exceeding the sublimation** temperature is reset to the sublimation temperature.

temperature : float, optional

The dust sublimation temperature, in K

set_sublimation_specific_energy(*mode*, *specific_energy=0.0*)
Set the dust sublimation mode and specific energy.

Parameters **mode** : str

The dust sublimation mode, which can be:

- 'no' - no sublimation
- **'fast' - remove all dust in cells exceeding the** sublimation specific energy
- **'slow' - reduce the dust in cells exceeding the** sublimation specific energy
- **'cap' - any specific energy exceeding the sublimation** specific energy is reset to the sublimation specific energy.

specific_energy : float, optional

The dust sublimation specific energy, in cgs

set_lte_emissivities(*n_temp=1200*, *temp_min=0.1*, *temp_max=100000.0*)
Calculate the emissivities assuming LTE

Parameters **n_temp** : int, optional

The number of temperatures to calculate the emissivities for

temp_min : float, optional

The minimum temperature to calculate the emissivities for

temp_max : float, optional

The maximum temperature to calculate the emissivities for

plot(*filename*)

read(*filename*)
Read in from a standard dust file

write(*filename*, *compression=True*)
Write out to a standard dust file, including calculations of the mean opacities and optionally thermal emissivities.

temperature2specific_energy(*temperature*)
Convert a temperature to its corresponding specific energy value.

Parameters **temperature** : float or array_like

The temperature to convert

Returns **specific_energy** : float or array_like

The specific energy corresponding to the input temperature

specific_energy2temperature(*specific_energy*)
Convert a specific energy value to its corresponding temperature.

Parameters **specific_energy** : float or array_like

The specific energy to convert

Returns **temperature** : float or array_like

The temperature corresponding to the input specific energy

chi_nu_temperature(*temperature*)
Compute the mean opacity to extinction for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_temperature(*temperature*)
Compute the mean opacity to absorption for a blackbody at a given temperature.

Parameters **temperature** : float

The temperature of the blackbody to use

Returns **kappa_nu_mean** : float

The mean opacity to absorption

chi_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to extinction for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **chi_nu_mean** : float

The mean opacity to extinction

kappa_nu_spectrum(*nu*, *fnu*)
Compute the mean opacity to absorption for a given spectrum.

Parameters **nu** : array_like

The frequencies, in Hz

fnu : array_like

The monochromatic fluxes per unit frequency. Units are unimportant since proportionality constants are cancelled out in the computation.

Returns **kappa_nu_mean** : float

The mean opacity to absorption

4.3 Contributing to Hyperion

Whether you are interested in contributing a bug or typo fix, improved documentation, tutorials, or new features, you can follow the instructions on this page!

The method described below is the preferred way of contributing to Hyperion. By following these instructions, you will ensure that you are properly credited for the changes in the Hyperion repository, and it will be much easier for the developers to review and merge in the changes. Therefore, please be patient and follow the step-by-step instructions and let us know if anything is unclear. If you are unable to follow these instructions for any reason, you *can* send us a tar file with updated code, but it will take a while to review the changes.

The instructions described here assume that you have git installed. We use the term *trunk* to refer to the main Hyperion repository.

Note: New to git? Fear not! Github has an excellent interactive tutorial here.

4.3.1 Creating a fork

You only need to do this the first time you want to start working on the Hyperion code.

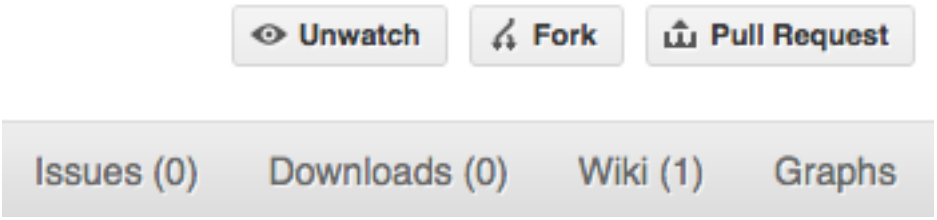
Set up and configure a GitHub account

If you don't have a GitHub account, go to the GitHub page, and make one.

You then need to configure your account to allow write access - see the *Generating SSH keys* help on GitHub Help.

Create your own fork of a repository

1. Log into your GitHub account.
2. Go to the Hyperion GitHub home.
3. Click on the *fork* button:



Now, after a short pause and some 'Hardcore forking action', you should find yourself at the home page for your own forked copy of Hyperion.

Setting up the fork to work on

1. Clone your fork to the local computer:

```
git clone git@github.com:your-user-name/hyperion.git
```

2. Change directory to your new repo:

```
cd hyperion
```

Then type:

```
git branch -a
```

to show you all branches. You'll get something like:

```
* master
remotes/origin/master
```

This tells you that you are currently on the `master` branch, and that you also have a `remote` connection to `origin/master`. What remote repository is `remote/origin`? Try `git remote -v` to see the URLs for the remote. They will point to your GitHub fork.

Now you want to connect to the Hyperion repository, so you can merge in changes from the trunk:

```
cd hyperion
git remote add upstream git://github.com/hyperion/hyperion.git
```

`upstream` here is just the arbitrary name we're using to refer to the main Hyperion repository.

Note that we've used `git://` for the URL rather than `git@`. The `git://` URL is read only. This means we that we can't accidentally (or deliberately) write to the upstream repo, and we are only going to use it to merge into our own code.

Just for your own satisfaction, show yourself that you now have a new 'remote', with `git remote -v show`, giving you something like:

```
upstream   git://github.com/hyperion-rt/hyperion.git (fetch)
upstream   git://github.com/hyperion-rt/hyperion.git (push)
origin     git@github.com:your-user-name/hyperion.git (fetch)
origin     git@github.com:your-user-name/hyperion.git (push)
```

Your fork is now set up correctly, and you are ready to hack away.

Deleting your master branch

It may sound strange, but deleting your own `master` branch can help reduce confusion about which branch you are on:

```
git branch -D master
```

See deleting master on github for details.

4.3.2 Updating the mirror of trunk

From time to time you should fetch the upstream (trunk) changes from github:

```
git fetch upstream
```

This will pull down any commits you don't have, and set the remote branches to point to the right commit. For example, 'trunk' is the branch referred to by (remote/branchname) `upstream/master` - and if there have been commits since you last checked, `upstream/master` will change after you do the fetch.

4.3.3 Making a new feature branch

When you are ready to make some changes to the code, you should start a new branch. Branches that are for a collection of related edits are often called 'feature branches'.

Making an new branch for each set of related changes will make it easier for someone reviewing your branch to see what you are doing.

Choose an informative name for the branch to remind yourself and the rest of us what the changes in the branch are for. For example `add-ability-to-fly`, or `buxfix-for-issue-42`.

```
# Update the mirror of trunk
git fetch upstream

# Make new feature branch starting at current trunk
git branch my-new-feature upstream/master
git checkout my-new-feature
```

Generally, you will want to keep your feature branches on your public github fork. To do this, you git push this new branch up to your github repo. Generally (if you followed the instructions in these pages, and by default), git will have a link to your GitHub repo, called `origin`. You push up to your own repo on GitHub with:

```
git push origin my-new-feature
```

4.3.4 The editing workflow

1. Make some changes
2. See which files have changed with `git status` (see git status). You'll see a listing like this one:

```
# On branch ny-new-feature
# Changed but not updated:
#   (use "git add <file>..." to update what will be committed)
#   (use "git checkout -- <file>..." to discard changes in working directory)
#
#    modified:   README
#
# Untracked files:
#   (use "git add <file>..." to include in what will be committed)
#
#    INSTALL
no changes added to commit (use "git add" and/or "git commit -a")
```

3. Check what the actual changes are with `git diff` (git diff).

4. Add any new files to version control `git add new_file_name` (see git add).
5. Add any modified files that you want to commit using `git add modified_file_name` (see git add).
6. Once you are ready to commit, check with `git status` which files are about to be committed:

```
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#    modified:   README
```

   Then use `git commit -m 'A commit message'`. The `m` flag just signals that you're going to type a message on the command line. The git commit manual page might also be useful.

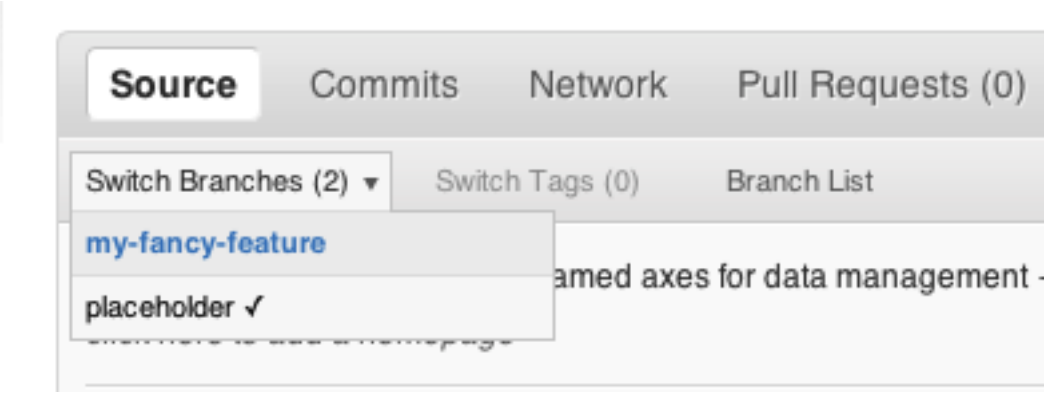
7. To push the changes up to your forked repo on github, do:

```
git push origin my-new-feature
```

4.3.5 Asking for your changes to be reviewed or merged

When you are ready to ask for someone to review your code and consider a merge:

1. Go to the URL of your forked repo, say `http://github.com/your-user-name/hyperion`.
2. Use the 'Switch Branches' dropdown menu near the top left of the page to select the branch with your changes:



3. Click on the 'Pull request' button:

   Enter a title for the set of changes, and some explanation of what you've done. Say if there is anything you'd like particular attention for - like a complicated change or some code you are not happy with.

   If you don't think your request is ready to be merged, just say so in your pull request message. This is still a good way of getting some preliminary code review.

4.3.6 Some other things you might want to do (advanced)

Delete a branch on github

```
# change to the master branch (if you still have one, otherwise change to
# another branch)
git checkout master

# delete branch locally
git branch -D my-unwanted-branch

# delete branch on github
git push origin :my-unwanted-branch
```

(Note the colon `:` before `test-branch`. See also: http://github.com/guides/remove-a-remote-branch

Several people sharing a single repository

If you want to work on some stuff with other people, where you are all committing into the same repository, or even the same branch, then just share it via github.

First fork Hyperion into your account, as from *Creating a fork*.

Then, go to your forked repository GitHub page, say `http://github.com/your-user-name/hyperion`

Click on the 'Admin' button, and add anyone else to the repo as a collaborator:

Now all those people can do:

```
git clone git@githhub.com:your-user-name/hyperion.git
```

Remember that links starting with `git@` use the ssh protocol and are read-write; links starting with `git://` are read-only.

Your collaborators can then commit directly into that repo with the usual:

```
git commit -am 'ENH - much better code'
git push origin master # pushes directly into your repo
```

Rebasing on trunk

Let's say you thought of some work you'd like to do. You *Updating the mirror of trunk* and *Making a new feature branch* called `cool-feature`. At this stage trunk is at some commit, let's call it E. Now you make some new commits on your `cool-feature` branch, let's call them A, B, C. Maybe your changes take a while, or you come back to them after a while. In the meantime, trunk has progressed from commit E to commit (say) G:

```
      A---B---C cool-feature
     /
D---E---F---G trunk
```

At this stage you consider merging trunk into your feature branch, and you remember that this here page sternly advises you not to do that, because the history will get messy. Most of the time you can just ask for a review, and not worry that trunk has got a little ahead. But sometimes, the changes in trunk might affect your changes, and you need to harmonize them. In this situation you may prefer to do a rebase.

Rebase takes your changes (A, B, C) and replays them as if they had been made to the current state of `trunk`. In other words, in this case, it takes the changes represented by A, B, C and replays them on top of G. After the rebase, your history will look like this:

```
              A'--B'--C' cool-feature
             /
D---E---F---G trunk
```

See rebase without tears for more detail.

To do a rebase on trunk:

```
# Update the mirror of trunk
git fetch upstream

# Go to the feature branch
git checkout cool-feature

# Make a backup in case you mess up
git branch tmp cool-feature

# Rebase cool-feature onto trunk
git rebase --onto upstream/master upstream/master cool-feature
```

In this situation, where you are already on branch `cool-feature`, the last command can be written more succinctly as:

```
git rebase upstream/master
```

When all looks good you can delete your backup branch:

```
git branch -D tmp
```

If it doesn't look good you may need to have a look at *Recovering from mess-ups*.

If you have made changes to files that have also changed in trunk, this may generate merge conflicts that you need to resolve - see the git rebase man page for some instructions at the end of the "Description" section. There is some related help on merging in the git user manual - see resolving a merge.

Recovering from mess-ups

Sometimes, you mess up merges or rebases. Luckily, in git it is relatively straightforward to recover from such mistakes.

If you mess up during a rebase:

```
git rebase --abort
```

If you notice you messed up after the rebase:

```
# Reset branch back to the saved point
git reset --hard tmp
```

If you forgot to make a backup branch:

```
# Look at the reflog of the branch
git reflog show cool-feature

8630830 cool-feature@{0}: commit: BUG: io: close file handles immediately
278dd2a cool-feature@{1}: rebase finished: refs/heads/my-feature-branch onto 11ee694744f2552d
26aa21a cool-feature@{2}: commit: BUG: lib: make seek_gzip_factory not leak gzip obj
...

# Reset the branch to where it was before the botched rebase
git reset --hard cool-feature@{2}
```

Rewriting commit history

Note: Do this only for your own feature branches.

There's an embarrassing typo in a commit you made? Or perhaps the you made several false starts you would like the posterity not to see.

This can be done via *interactive rebasing*.

Suppose that the commit history looks like this:

```
git log --oneline
eadc391 Fix some remaining bugs
a815645 Modify it so that it works
2dec1ac Fix a few bugs + disable
13d7934 First implementation
6ad92e5 * masked is now an instance of a new object, MaskedConstant
29001ed Add pre-nep for a copule of structured_array_extensions.
...
```

and `6ad92e5` is the last commit in the `cool-feature` branch. Suppose we want to make the following changes:

- Rewrite the commit message for `13d7934` to something more sensible.
- Combine the commits `2dec1ac`, `a815645`, `eadc391` into a single one.

We do as follows:

```
# make a backup of the current state
git branch tmp HEAD
# interactive rebase
git rebase -i 6ad92e5
```

This will open an editor with the following text in it:

```
pick 13d7934 First implementation
pick 2dec1ac Fix a few bugs + disable
pick a815645 Modify it so that it works
pick eadc391 Fix some remaining bugs

# Rebase 6ad92e5..eadc391 onto 6ad92e5
#
# Commands:
#  p, pick = use commit
#  r, reword = use commit, but edit the commit message
#  e, edit = use commit, but stop for amending
#  s, squash = use commit, but meld into previous commit
#  f, fixup = like "squash", but discard this commit's log message
#
# If you remove a line here THAT COMMIT WILL BE LOST.
# However, if you remove everything, the rebase will be aborted.
#
```

To achieve what we want, we will make the following changes to it:

```
r 13d7934 First implementation
pick 2dec1ac Fix a few bugs + disable
f a815645 Modify it so that it works
f eadc391 Fix some remaining bugs
```

This means that (i) we want to edit the commit message for `13d7934`, and (ii) collapse the last three commits into one. Now we save and quit the editor.

Git will then immediately bring up an editor for editing the commit message. After revising it, we get the output:

```
[detached HEAD 721fc64] FOO: First implementation
 2 files changed, 199 insertions(+), 66 deletions(-)
[detached HEAD 0f22701] Fix a few bugs + disable
 1 files changed, 79 insertions(+), 61 deletions(-)
Successfully rebased and updated refs/heads/my-feature-branch.
```

and the history looks now like this:

```
0f22701 Fix a few bugs + disable
721fc64 ENH: Sophisticated feature
6ad92e5 * masked is now an instance of a new object, MaskedConstant
```

If it went wrong, recovery is again possible as explained *above*.

4.4 Version History

4.4.1 0.9.7 (2015-08-22)

New features

- Added support for on-the-fly filter convolution. [#119]
- Power-law and Ulrich envelopes can now be used on cylindrical polar grids. [#136]
- Provide a way to sample random positions inside Voronoi cells. [#134, #151]

- Added the ability to load AMR grids from yt datasets. [#148]

Bug fixes

- Correctly raise an error if photons are emitted outside the Voronoi grid. [#127]
- Avoid issues with number of photons when reading in models. [#145]
- Fix a bug that caused sublimation parameters to not be correctly read in. [#133]
- Fixed Fortran dependencies install script.

API changes

- `set_aperture_range` has been renamed to `set_aperture_radii` to emphasize that these are radii. [#132]

Other

- Internal refactoring of how spectra are gridded for raytracing to make it easier to implement Doppler-shifted spectra in future. [#126]
- Optimizations to memory and disk usage for Voronoi grids. [#128, #154, #156]
- Improvements to warnings and documentation. [#54, #98, #125]
- Removed deprecated mctherm2hyperion script. [#144]

4.4.2 0.9.6 (2015-02-27)

Bug fixes

- Fixed backward compatibility with files that don't include d_min/d_max

4.4.3 0.9.5 (2015-02-17)

New features

- Added an importer function, `construct_octree`, to convert a list of SPH particles into an Octree grid. [#67]
- Addded support for Voronoi grids. Voronoi grids can be set via the *~hyperion.model.Model.set_voronoi_grid* method, passing in the `x`, `y` and `z` coordinates of the sites as arguments. [#92]
- Added the ability to make images that split up photons as a function of how many times they were scattered (using `set_track_origin('scatterings')`). [#99]
- Added the ability to kill photons when scattered using `set_kill_on_scatter`, similarly to the existing `set_kill_on_absorb`. [#101]
- Added the ability to use input files in `ModelOutput.get_quantities`. [#106]
- Added the ability to control the interpretation of the specific energy passed to `add_density_grid` using the `set_specific_energy_type` argument. [#117]

- Added the ability to use a grid from an HDF5 file on disk without reading it into the Python code, using `use_grid_from_file`. [#116]
- Added support for cmake. [#112]
- `Image` and `SED` objects now include attributes `d_min` and `d_max` that indicate the depth of the region used to contruct the image or SED. [#121]
- Fixed a bug in the computation of the Rosseland mean opacity (it was in fact the Planck reciprocal mean opacity). Dust files have now been updated to version 2 to include both the Rosseland mean opacity and the Planck reciprocal mean opacity. [#123]

Bug fixes

- Fixed a minor bug in the logic for killing photons that have had too many interactions. [#100]
- Fixed a bug that meant that BipolarCavity instances could not be subtracted from AmbientMedium instances. [#106]

Other improvements

- The `to_yt()` methods are now compatible with yt 3.x (3.0.1 and later recommended). [#113]
- The `uncertainties=True` mode for `get_sed` and `get_image` has now been properly vectorized and should be faster by a factor of a few when requesting polarization results. [#114]

4.4.4 0.9.4 (2014-01-29)

New features

- Image and SED groups now have a `set_stokes` option that allows users to specify whether to save Stokes componenets other than I. Prior to this version, all Stokes components were always saved, but this resulted in an unecessarily high memory usage in many cases, so the default is now set to *False*, and users have to explicitly set `set_stokes(True)` in order to save all Stokes components. [#61]
- It is now possible to turn off the warnings that occur when photons are killed due to too many interactions, using the `warn=True/False` option for the *`set_max_interactions()`* method (and other similar methods). [#68]

Bug fixes

- Fix Fortran dependency installer for gfortran 4.5 and earlier
- Fixed a bug that caused models using the monochromatic radiative transfer settings to not be read in correctly by *`read()`*. [#78]

API Changes

- When using the monochromatic radiative transfer mode, users should now use the *`set_wavelength_index_range()`* method instead of *`set_wavelength_range()`*. [#78]

4.4.5 0.9.3 (2013-11-14)

New features

- For models that require many point sources with a common spectrum, a new source type (point source collection) is now available. To add a point source collection, use:

```
source = m.add_point_source_collection()
```

  The `source.luminosity` attribute should be set to an array with as many elements as sources, and the `source.position` attribute should be set to a 2-d array where the first dimension matches `source.luminosity`, and with 3 elements in the second dimension (x, y, and z).

- Sources can now be given names as strings, which can then be used as an argument to `source_id` in *`get_sed()`* and *`get_image()`* (when using photon tracking).
- Improved documentation to explain better in which cases dust and total densities should be used. This is summarized in Important Notes.
- Added an option to specify the minimum (relative) radial cell spacing for the *`AnalyticalYSOModel`* class.
- Fixed bug that prevented users from setting the grid manually with the *`AnalyticalYSOModel`* class.
- It is now possible to include multiple ambient mediums with different dust properties (this was limited to a single ambient medium property previously).
- The *`add_density_grid()`* method can now be called with a grid view for all grid types (previously this was only possible for AMR grids).
- Added dust classes to the API documentation.
- Fixed a typo in the equation for the *`AlphaDisk`* class, and added definitions of the scaleheight for *`AlphaDisk`* and *`FlaredDisk`*.
- Improve the reliability of the configure script.

4.4.6 0.9.2 (2013-08-16)

New Features

- *`get_sed()`* and *`get_image()`* now return SED and Image objects that contain meta-data in addition to the data itself. For example, images contain information about the field of view (in physical/angular units, where appropriate), and information about the units is also included. The old syntax of `wav, nufnu = m.get_sed(...)` will still work, but the meta-data will not be accessible in those cases.
- New library of dust models, accessible in Library of dust models
- It is now possible to read in previous models completely, including the density structure, geometry, sources, dust, and configuration, using the *`read()`* method. In addition, new methods individual methods *`use_sources()`*, *`use_image_config()`*, *`use_run_config()`*, and *`use_output_config()`* allow more detailed control over reading in parameters from previous models.
- It is now possible to force overwrite Hyperion output from the command-line using the `-f` option:

```
hyperion -f input output
```

  or when using the individual fortran binaries:

```
mpirun -n 8 hyperion_car_mpi -f input output
```

This will likely be useful for users of computer clusters who don't want a job to fail just because the output file already exists.

- Regular Cartesian grids can now also be exported for viewing in yt (as was previously possible for AMR and Octree grids).
- A new function, *run_with_vertical_hseq()*, is available to help with the calculation of vertical Hydrostatic equilibrium in disks. Note that this feature is still experimental and should be used with care.
- A new function, *tau_to_radius()*, is available to compute, for spherical polar grids, the optical depth from infinity to a given radius.

Improvements

- PyFITS, PyWCS, and ATpy are no longer required for Hyperion. Instead, the Astropy package is now required as a dependency.
- Updated download link for MPICH2
- The `rho_0` attribute for disks is now a property, not a method, and can be set by the user instead of the disk mass.
- The documentation has been improved and fixed in places thanks to user feedback.
- AnalyticalYSOModel instances are no longer 'static' once they have been written out (this means one can write out a model, change a parameter, and write out a new different model, which was not possible previously).
- The Fortran code now reads in dust models faster because it computes all cumulative distribution functions more efficiently.
- Statistics for killed photons are now kept for each iteration rather than just summing all of them.

Bug fixes

- Fix compatibility with Numpy 1.8.0.dev
- Fix coverage testing for Python 3
- Fixed an issue which caused temporary files to not be deleted after running tests.

API changes

- The `AnalyticalYSOModel.evaluate_optically_thin_radii()` method has been removed.

4.4.7 0.9.1 (2012-10-26)

New Features

- Updated hyperion2fits to extract binned images
- Added wmax= option for AnalyticalYSOModel.set_cylindrical_grid_auto

Improvements

- Made deps/fortran/install.py script more robust to architecture, and to lack of zlib library.
- Ensure that spectrum always gets converted to floating-point values
- Give a more explicit error message if optical properties for dust are not set.

Bug fixes

- Fixed bug that prevented BipolarCavity from being used
- Ensure that get_quantities works even if no initial iterations were computed
- Fix scattering for cases where P2=0. The code could sometimes crash if a mix of isotropic and non-isotropic dust was used (reported by M. Wolff).
- Fix a bug that occurred when outputting multiple images with the depth option (reported and fixed by T. Bowers) [#21, #22]

4.4.8 0.9.0 (2012-07-27)

- Initial public release.

CHAPTER 5

Credits

Hyperion is currently being developed by Thomas Robitaille.

Interested in contributing fixes or patches to the code or documentation? Read Contributing to Hyperion for more details! If you are interested in developing new features, contact me and we can discuss how to coordinate efforts.

A great thanks to the following users whose help with testing early versions of Hyperion was invaluable:

- Katharine Johnston
- Nils Lippok
- Stella Offner
- Sarah Ragan
- Andrew Schechtman-Rook
- Amy Stutz
- Barbara Whitney
- Mike Wolff

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